11-1-1994

Hydrogeological and Hydrochemical Characterization of the Matozinhos-Pedro Leopoldo Karst, Brazil

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HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION OF THE MATOZINHOS-PEDRO LEOPOLDO KARST, BRAZIL

A Thesis

Presented to

the Faculty of the Department of Geography and Geology

Western Kentucky University

Bowling Green, Kentucky

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Augusto S. Auler

November 1994

HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION OF THE

MATOZINHOS-PEDRO LEOPOLDO KARST, BRAZIL

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ACKNOWLEDGEMENTS

This work was only possible thanks to the financial support of Richmond Area Speleological Society, Cave Research Foundation and National Speleological Society. A significant part of the research was performed with equipment and material from the Department of Geography and Geology, Western Kentucky University. Dr. Nick Crawford, my advisor, was very helpful in arranging for the needed equipment. The graduate students at the Center for Cave and Karst Studies of WKU helped in the initial stages of the thesis proposal. I am indebted to the staff of the Department and especially to Dr. Chris Groves and Dr. Kenneth Kuehn for the support and helpful comments. During my long period away from Brazil, several people helped me feel at home -- to name a few, Bill Howcroft, Jim Smith, Tammie Heazlit, Greg Pierce and others. Special thanks go to my friends Julia and Jim Magnusson from Minneapolis for the constant help in all phases of my graduate work.

During the extensive field work, I received substantial support from a number of people and sources. My caving partners of Grupo Bambuí de Pesquisas Espeleológicas assisted me in many of the observations and dye traces. I am especially grateful to Heloisa Neves, Paulo Pessoa and Luis Piló for their assistance during water sampling and dye traces. Adriana Paiano provided constant help throughout the research and writing of this thesis. The current meter was kindly lent by the Museum of Natural History of Federal University of Minas Gerais, through Professor Heinz Charles Kohler. CEMIG provided orthogonal aerial photographs at discount prices. Mylene Berbert-Born, Maria Letícia Patrus of CPRM and Arnaldo Carvalho helped with speleological, meteorological and lab data. NAE (Núcleo de Atividades Espeleológicas) allowed me to use the map of Couvelabro Cave. I am grateful to Cimento Mauá SA and its director, Frank Davis, for allowing me to use data collected during professional work in their area. Thanks also is extended to the many farmers for permitting access to their properties during sampling and dye tracing. A draft of this thesis was critically reviewed by H.C. Kohler, L. Piló and P. Pessoa. Finally, I must recognize that nothing would be accomplished without my parents firm encouragement in all my life's decisions.

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HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION OF THE MATOZINHOS-PEDRO LEOPOLDO KARST, BRAZIL

Augusto S. Auler November, 1994 110 Pages

Directed by: Dr. Nicholas Crawford, Dr. Christopher Groves, and Dr. Kenneth Kuehn

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The Matozinhos-Pedro Leopoldo limestone area is a tropical karst located near the metropolis of Belo Horizonte, East Central Brazil, in an area undergoing rapid urbanization and land degradation. Qualitative dye tracing experiments have determined the groundwater routes and catchment areas in the two major drainage basins in the area, Samambaia Basin and Palmeiras-Mocambo Basin. Other drainage basins were identified, but not traced due to the absence of related swallets. Fluorescein and optical brightener had a poor performance as tracers under tropical climate. Dilution due to the existance of lakes at some swallets prevented some dye traces. The water that flows through this karst area is almost entirely autogenic, having a small external contribution from some phyllite areas. About 88% of the total water discharge of identified springs drains directly toward Velhas River, the regional base level. The remaining 12% drains toward Mata Creek, a tributary of the Velhas River.

Hydrochemical monitoring in four of the major springs showed that groundwater quality for the measured parameters in the discharge zone is generally good, despite the heavy industrialization and occupation in some of the recharge areas. Conduit flow predominates in Samambaia and Palmeiras-Mocambo Basins. The outlets for these basins show a marked seasonal variation in the physical and chemical parameters monitored. Some of the other springs such as Moinho Velho Spring and Jaguara Spring show little variation in temperature, suggesting a diffuse flow component. All springs are characterized by hardness dilution during the wet season, suggesting a small residence time during the wet season, not allowing the water to achieve saturation. Seasonal variation in runoff is the most important control on the hydrochemical pattern of the area. It determines the marked dilution of major ions in both conduit-flow and diffuse-flow springs. Variation in soil CO_2 due to the rainfall pattern may also play an important role in the water chemistry.

Observation of paleoflow indicators made in several dry caves showed that the past flow pattern at Palmeiras-Mocambo Basin agrees with the present groundwater routes. At Samambaia Basin, however, the lower reaches of the basin show paleoflow directions pointing toward other active base levels such as Mocambeiro Depression or Velhas River, suggesting that Samambaia Basin may have developed its present morphology in a latter stage.

CHAPTER 1 INTRODUCTION

The study of karst terrains has had a slow development in Brazil during the past 160 years. The same cannot be said about the urban development. The high population growth has accelerated human occupation in many areas. Pressure on the environment is increasing throughout Brazil, and karst areas are among the most vulnerable.

The study area is located 40 km northeast of Belo Horizonte, the fourth largest city in Brazil, with 2.0 million inhabitants (Figure 1.1). Five medium-sized cities occur in the surroundings of the area. Their populations according to the 1991 census are: Lagoa Santa: 24,026; São José da Lapa: 6,841; Pedro Leopoldo: 30,257; Matozinhos: 21,474 and Vespasiano: 29,000 (IBGE, 1991). There are also many other smaller villages. The estimated population living upon the karst area is about 25,000 people. The total surface of the studied area is approximately 250 km^2, bringing population density to about 100 people/km^2, surely one of the highest among Brazilian karst areas.

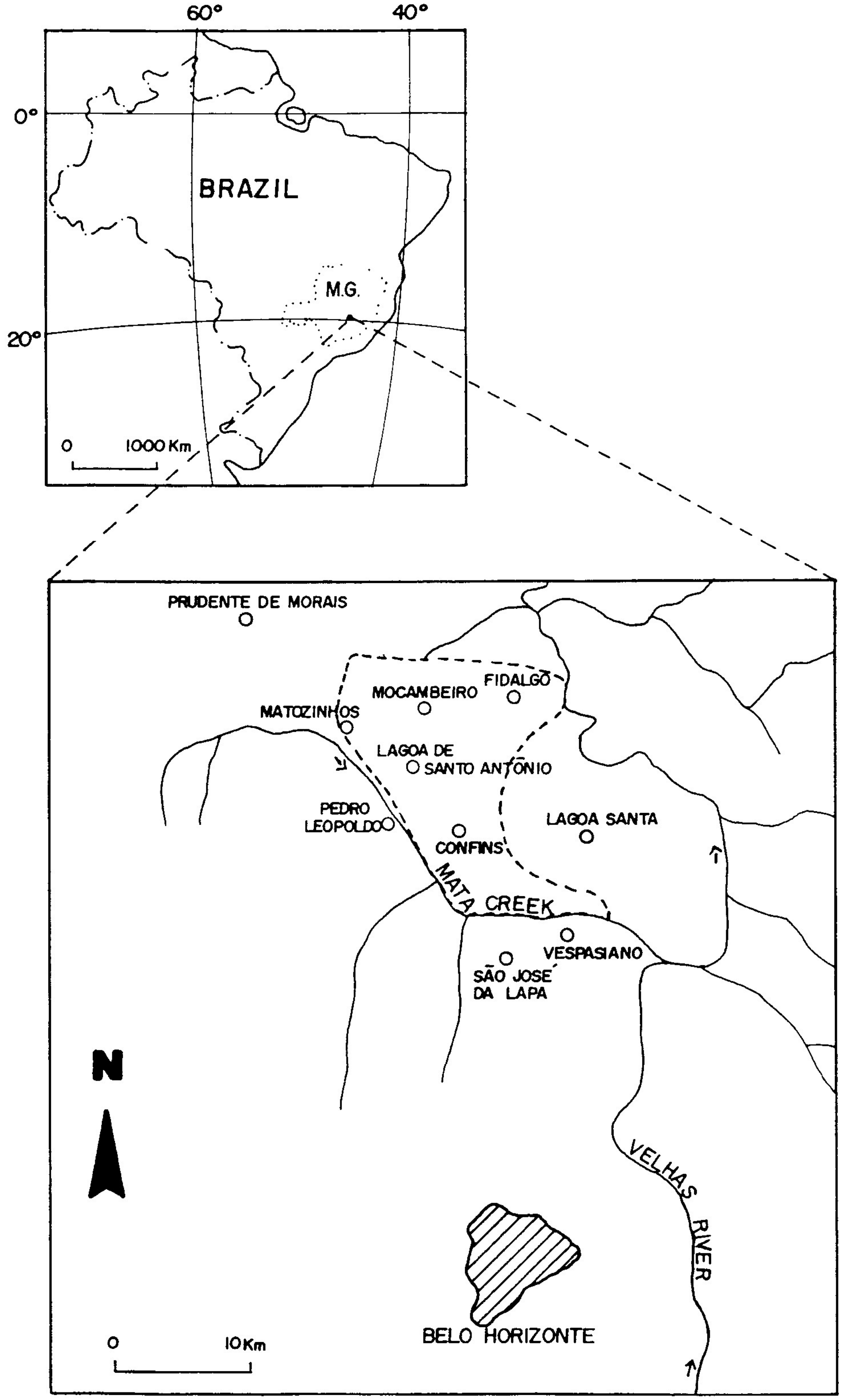


Figure 1.1 Location of the Study Area

The proximity to Belo Horizonte has attracted many industries to the region. Limestone mining for cement production is widespread and most of the karst region belongs to mining companies. Cattle and agricultural farming still exist, although they are being rapidly suppressed by industries and urbanization.

Previous studies have referred to this area as the Lagoa Santa Karst (Kohler, 1989). This is due to the fact that, during the last century, the first scientists chose Lagoa Santa as a convenient base for studying the area. Lagoa Santa, built over phyllitic rocks, was at that time the best developed town. In this thesis I will refer to this karst region as the Matozinhos-Pedro Leopoldo karst area. Most karst landforms occur inside the boundaries of these two municipalities. As the population increases, more villages will become cities, and probably the area will be surrounded by other municipalities.

This study is one of very few done on karst hydrology in Brazil. It is the first to use a series of dye tracing experiments to survey groundwater flow routes. The hydrology of Matozinhos-Pedro Leopoldo Karst was regarded as a "black box" before this study. The general purpose was to gain a first view on the groundwater behavior.

This thesis comprises three separate but related studies. Chapters Two and Three give a general introductory view on the geography and karst landforms. The heart of the thesis is formed by Chapters Four, Five and Six. These chapters deal with different aspects of the karst hydrology. Chapter Four summarizes the groundwater flow in the area inferred from water tracing experiments. Chapter Five gives an account of the hydrochemistry at some selected springs. Chapter Six deals with the paleodrainage, deduced from solution features in dry cave conduits. These three chapters help built an overall picture of the hydrogeology in the Matozinhos-Pedro Leopoldo karst. A general conclusion ends the thesis.

CHAPTER 2 NATURAL SETTING

2.1 Geology

The karst is developed upon crystalline limestones of Sete Lagoas Formation, Bambui Group. In the outcrops it is a pure limestone with less than 3% of noncarbonate residue (Marchese, 1974). The limestone shows thin, nearly horizontal lamination, with a gentle dip to the east (IGA, 1982). It was deposited in a shallow sea that occupied a stable craton during the Proterozoic Eon. Radiometric dating and stromatolite analysis place carbonate deposition between 900 and 600 million years ago (Inda et al., 1984). The carbonates overlie gneisses and migmatites (Figure 2.1). Phyllites occur over the limestone in the highest portions of the area.

Figure 2.2 shows the geologic map of the area. Limestone extends to the northeast while phyllites and high-grade metamorphic assemblages limit the carbonates in other directions. The carbonates of Sete Lagoas Formation were deposited over a highly irregular crystalline bedrock. The

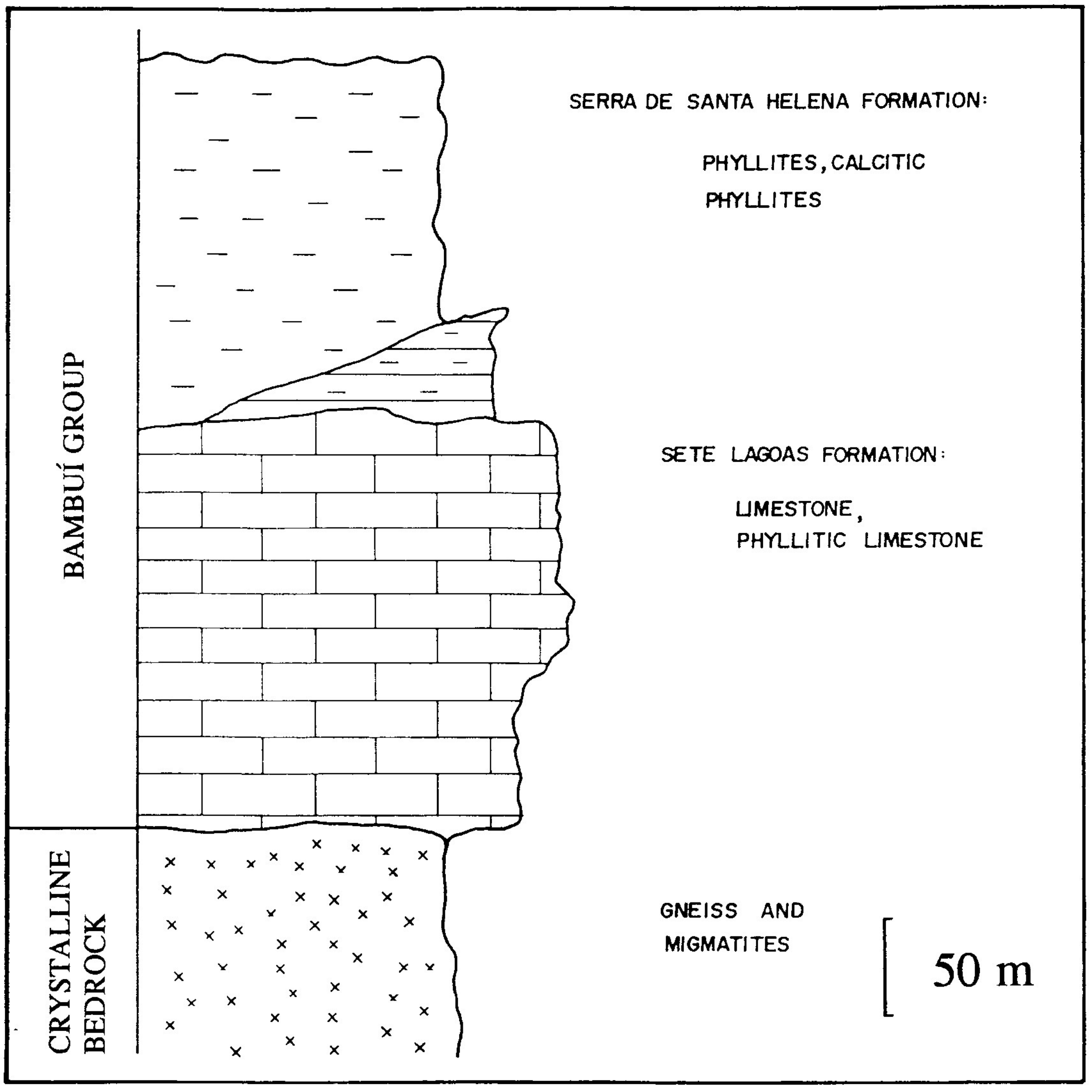


Figure 2.1 Stratigraphic Column for the Area. Adapted from CPRM (1992)

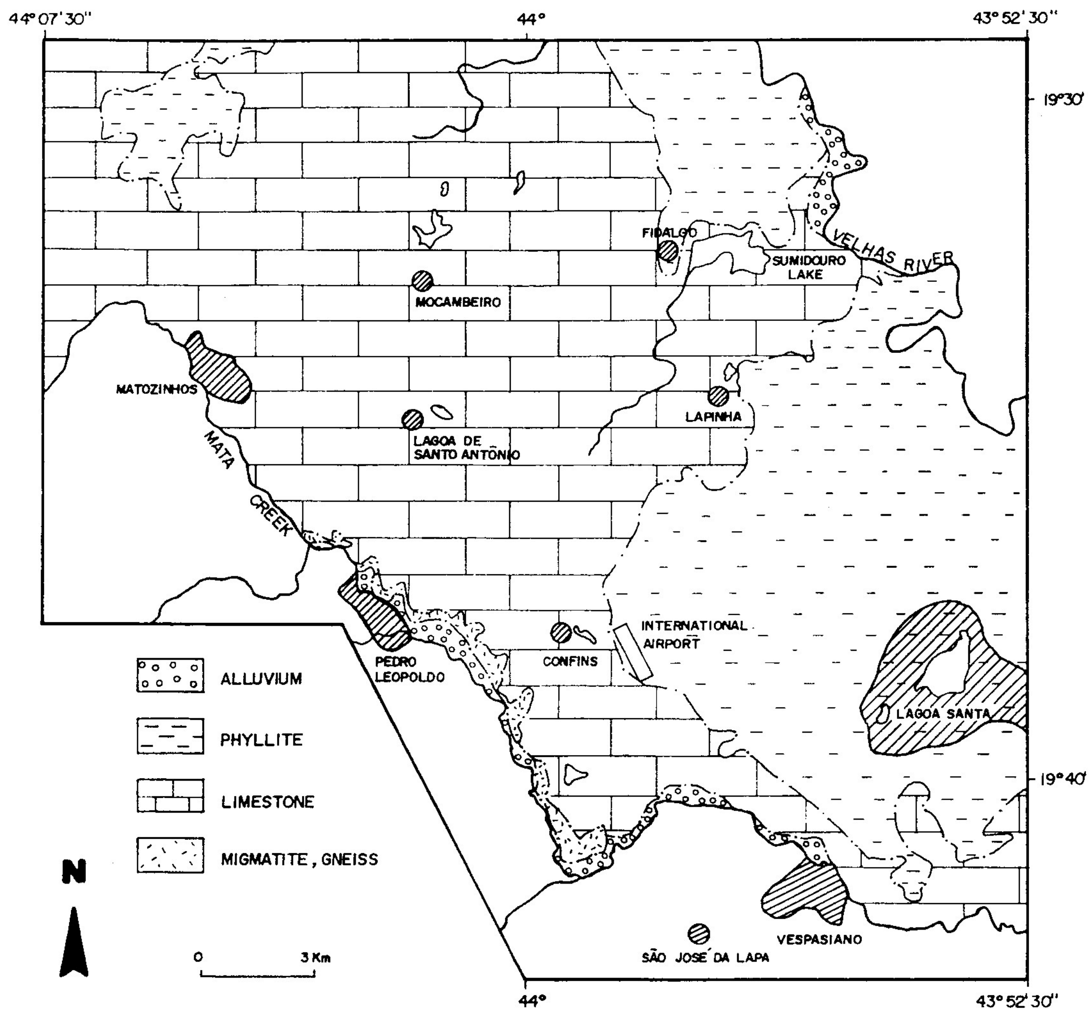


Figure 2.2 Geological Map of the Area. Adapted from Silva et al. (1987)

limestone thickness varies between approximately 250 m in the highest portions of the area to about 50 m in the low plains.

The limestone shows a well-marked joint pattern produced during the Brasiliano orogenic event (550 Ma). The more common joint directions as inferred from aerial photographs are N10-28E and N50-69E (Silva et al., 1987). Apart from vertical lithological variations, the limestone is quite homogeneous throughout the study area.

2.2 Physiography

Velhas River, at the northeastern boundary of the area, is the major base level. A tributary, Mata Creek, limits the area in the southern and southwestern boundaries. Mata Creek flows into a alluvium-filled valley developed mainly over gneiss.

Silva et al.(1987) recognized eight physiographic domains in the area. In this thesis these are summarized in six domains: Karst High Plains; Mocambeiro Depression; Covered Karst Surfaces; Phyllite Surfaces; Fluvial Plains; and Igneous and Metamorphic Domain (Figure 2.3). This study was performed in the first two domains.

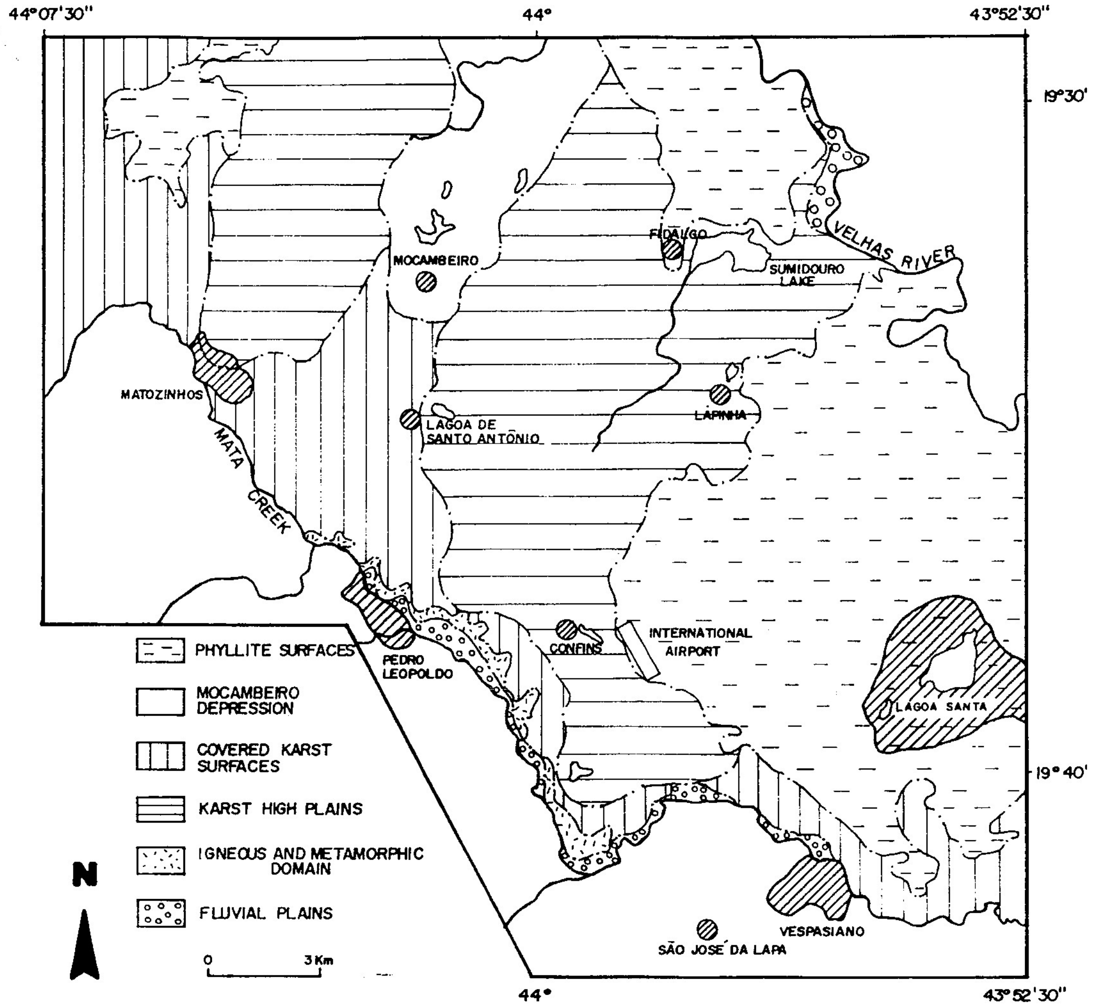


Figure 2.3 Physiographic Domains in the Area

The best developed karst topography occurs in the Karst High Plains. They comprise two areas separated by the Mocambeiro Depression. This domain is highly permeable, showing typical tropical karst landforms and underground drainage. This surface occurs between the elevations of 700 m and 860 m above sea level.

The Mocambeiro Depression is a much more dissected surface, elongated in the SW-NE direction. It is the lowest area in the karst, usually below 700 m. It can be characterized as a highly dissected karst, presently at a fluviokarst stage, with springs, surface streams and lakes.

The Covered Karst Surfaces exist where a thick mantle of soil overlies the limestone. Karst landforms are generally of limited expression. This domain occurs along Mata Creek, limited by the Phyllite Surfaces. Some well-developed surface karst is located south of Lagoa Santa.

The Phyllite Surfaces occur in the higher altitudes, usually above 800 m. It forms a gentle relief that masks the limestone. The Fluvial Plains develop along the major rivers, such as Mata Creek and Velhas River. The Igneous and Metamorphic Domain has a limited expression, forming rounded slopes along Mata Creek.

2.3 Climate

The Matozinhos-Pedro Leopoldo Karst is characterized by a well marked wet period during the summer (from October to March). These months receive nearly 90% of yearly rainfall. The wettest month is either December or January. The dry period extends from April to September. The average annual rainfall at the Raul Soares bridge over Velhas river is 1,265 mm (data from 1973-1990). At Pedro Leopoldo meteorological station the average annual rainfall reaches 1,284 mm (data from 1942-1990).

The mean annual temperature at Lagoa Santa is 22.8°C (data from 1961-1970 and 1987-1990). The highest temperatures during summer are in the upper 30's. The lowest temperatures during winter reach around 7°C. The mean annual humidity at Lagoa Santa is 68%.

CHAPTER 3 THE KARST TERRAIN

3.1 Karst Landforms

3.1.1 Surface Karst

The tropical karst of Matozinhos-Pedro Leopoldo shows a well-developed karst topography. The small magnesium content of the limestone and general lack of impurities favor limestone dissolution (Rauch and White, 1970;1977). The karst is capped either by phyllite or soil which is being rapidly eroded. Exposed limestone presently occurs at the tops and borders of some hills and at the face of limestone cliffs. While Journaux (1977) believed the Matozinhos-Pedro Leopoldo Karst is little developed because it is young, Balasz (1984) called it a paleokarst being exhumed at present time. The description of karst landforms that follows shows that the Matozinhos-Pedro Leopoldo Karst is a mature karst possessing a full range of karst landforms.

The first detailed description of the surface geomorphology in the area was made by Tricart (1956). Before him, most scientists had focused their studies upon the caves and their associated deposits. Tricart's pioneering work contains some inaccuracies especially concerning the geological framework of the area. He did not provide a well-balanced description of the landforms, their morphogenesis or frequency of occurrence. King (1956), in a regional study of planation surfaces in eastern Brazil, stated that karstification began in the Late Tertiary, related to an erosion cycle associated with Velhas River. During the late 1970's, more systematic work took place. A map of the area karst features, produced by a joint French-Brazilian team, was the starting point for a number of studies (e.g. Kohler, 1989). In the description of the map, Coutard et al. (1978) gave a brief but much improved general view of the karst geomorphology.

The Matozinhos-Pedro Leopoldo area contains good examples of most basic types of karst landforms. Some of these are widespread throughout Brazil, while others are characteristic of the region. The small-scale dissolution forms, known as karren, are well distributed in the area. Aerial karren such as rillenkarren and rinnenkarren (Bögli, 1960) occur on the denuded high portions of some hills. Tricart (1956) made an extensive description of several karren types. Among them he described the joint karren, a horizontal type of karren developed over a weakness zone. The joint karren is perhaps the most frequent aerial karren form, favored by the horizontal lamination of the limestone. Deckenkarren (karren formed by the action of plants) is found where roots penetrate the limestone. Kamenitza, shallow basin-like features due to both biologic and chemical dissolution, was observed in some selected outcrops.

Soil-covered karren has widespread occurrence in the area. Subsurface karren can be observed in the many quarries throughout the area. They can be sediment-filled depressions up to 5 m deep, with an assemblage of intercalated pinnacles. Since large sections of terrain are having the soil leached away, rounded karren forms (sometimes the tops of pinnacles) are exposed in several places.

The sinkholes (or dolines) are the most frequent landform in the area, despite the fact that previous studies (Tricart, 1956) have claimed that they are not. They are well-represented in all karst domains, especially into the High Plains. Journaux (1977) stated that there are no dissolution sinkholes in the area. However, this is probably the dominant sinkhole genetic subtype. Solution sinkholes have a gentle profile. They range from a few meters to more than a hundred meters in width, and their depth is usually less than half the total width. They can be rounded but usually there is a limestone outcrop at one side, producing an irregular shape and profile. As a sinkhole evolves, it can merge with nearby sinkholes. Smaller sinkholes also occur inside major ones. The bottoms of the sinkholes are usually capped with fertile soils, which are used for agriculture. Sometimes there is a cave entrance at one side.

Collapse sinkholes were observed in many locations. They have a much higher vertical dimension, with steeper sides, and are smaller in area. Many show signs of recent soil collapse. Some are associated with the underground drainage. Some ancient collapse sinkholes may have their profiles masked by later solution and soil covering processes. In the Mocambeiro Depression, the sinkholes are large and shallow, usually filled by temporary lakes. The frequency of sinkholes increases at higher altitudes.

Some large depressions occur in the area. Most of them - such as Macacos Depression and Sumidouro Lake are interpreted as mature sinkholes - the former generated by coalescence of sinkholes and the latter modified by fluvial processes. Another type comprises depressions on phyllite such as Lagoa Santa. This lake occupies a large depression up to 4 km^2 in area. It was studied by Kohler (1978) and Parizzi (1993). The genesis is probably due to slow subsidence triggered by the dissolution of the underlying limestone. The Mocambeiro Depression is the largest one in the area. It is more than 10 km long and about 1.5 km wide, and it is lower in elevation towards the Velhas River. Relict limestone towers (hums) such as Vargem da Pedra and Experiência da Jaguara (Coutard et al., 1978) are being dissolved. The Mocambeiro Depression has been interpreted as a polje (Auler, 1988; Kohler, 1989).

Fluvial processes are active in the study area. A few blind valleys exist, such as the first swallet of Palmeiras Creek. Dry valleys are nearly absent. The lower areas of

Mocambeiro Depression show a fluviokarst controlled by Jaguara/Mocambo Creek. The surface portion of Samambaia Creek, between Engenho Farm and Sumidouro Lake, is also a good example of fluviokarst.

Imposing limestone cliffs are the most characteristic landform in the area (Coutard et al., 1978). They comprise abrupt vertical to nearly vertical cliffs up to 60 m high, along one side of the sinkholes. External speleothems (anemolites) occur in some cliffs. Lakes and caves are common at the base of the cliffs. The genesis of the limestone cliffs is believed to be related to differential dissolution by a swallet or lake (Journaux, 1977). Breakdown is a secondary process. The distribution of the cliffs suggests that defined sets of master joints may play an important role. The orientation of the cliffs is related to the regional groundwater flow routes.

3.1.2 Underground Karst

So far, more than 300 caves have been registered in the area (SBE, 1993). The majority of them are dry and short. The longest mapped cave is Lapa Vermelha I, at 1,870 m. The caves are basically horizontal with few noteworthy vertical ones. The deepest is the 75 m deep Morro Redondo Cave. The depth potential is severely limited by the limestone thickness and base level. Caves more than 100 m deep are unlikely to exist.

The Matozinhos-Pedro Leopoldo Karst is the best explored karst area in Brazil. The speleological activities date back to the 1800's. A few caving clubs based at Belo Horizonte and Ouro Preto have been working in the area for decades. The rate of new discoveries is still high, although major finds are becoming rare.

Peter Lund, a Danish paleontologist, was the first to describe the caves in the area. Between the years of 1835 and 1844 he explored nearly 1,000 caves (Burmeister, 1853). Lund and his team produced the first cave maps in Brazil. Lund (1837) believed the caves were formed at a time when the limestone was covered by a sea or a big lake. The caves would have been generated by the action of waves. In a later paper (Lund, 1844), he presented a new mechanism for cave genesis. In his model, the caves were formed by downward percolation of water through the overlying phyllite into the limestone, followed by the infilling of the cavities by phyllitic sediment. The continuous uncovering of the limestone would then have favored a horizontal flow of water into the caves, excavating the sediment and forming more recent deposits. Lund paid special attention to the sediments inside the caves, since he was interested in the paleontological remains. He described in detail the processes of precipitation of speleothems and deposition of clastic sediments.

Liais (1872) also made remarks about the caves in the area. He described their genesis by groundwater as it moved through faults and joints. According to this author, the variable dimension of cave passages is due to the variation in the limestone composition, the most soluble paths being enlarged first. Liais (1872) recognized that large caves are rare in the area and, like Lund, concluded that two separate events of water flow and sediment deposition had taken place. He also made extensive observations on the chemical and clastic deposits.

Few studies about the caves have been performed during the 1900's. King (1956) identified two periods for the infilling of caves. According to him, the older sediments were of Late Pliocene age, while the younger ones, deposited over a calcite layer, were from the Late Pleistocene. Hurt & Blasi (1969) believed that a significant part of the speleothems was deposited between 7,000 and 4,500 BP during a wet period. Cave exploration and mapping started to become frequent after 1981, with the booming of caving clubs. The first systematic study on the speleogenesis was made by Piló (1986). He determined that 57% of his total sample of 53 caves are located inside sinkholes, 59% of these near the bottom. Dry caves comprised 55% of the total sample. Most of the active systems are drained by lakes and only 9% contain an active stream, according to the same author. Auler (1988) made a descriptive study of the caves. According to him most caves occur in the High Plains with phreatic caves being the most common type. Branchwork and network caves are both frequent. In a statistical study of the orientation of cave passages in the area, Beato et al.(1992) determined that most of the passages develop along N75-85E and N-S joints. Breakdown is present in only a few of the caves and appears not to play a significant role in the morphogenesis.

3.2 Karst Hydrology

The hydrology of the area comprises a free surface carbonate aquifer limited at the base by impermeable gneissic rocks. Some locally perched aquifers exist on the phyllite and above some clay-capped lakes. Groundwater flows toward two base level rivers. To the northeast, the Velhas River is the principal outlet for karst water. To the southwest, the Mata Creek drains some of the water.

There are two major drainage basins in the area. The Samambaia Creek Basin and the Palmeiras-Mocambo Creek Basin both drain toward the Velhas River. They have both surface and underground sections. The hydrology of these creeks will be detailed in the following chapter. Lund (1837) was the first to describe the high frequency of lakes in this karst area. They are more frequent in the Mocambeiro Depression. At least three types of lakes can be recognized: lakes over phyllite, sinkhole lakes and water table lakes, with the last two types developed over limestone bedrock. Sinkhole lakes are located in the upper portions of the area, at the bottoms of deep dolines. Water table lakes occur at the lower elevations, especially in the Mocambeiro Depression. The hydrologic behavior of the lakes is complex. Some are stable (phyllite lakes) while the others fluctuate, even drying up on rare occasions. The water level in these lakes is probably related both to rainfall and the input of sediment which plugs the lake outlet.

Lanari (1909) was the first to produce a detailed description of the hydrology. Before him, other scientists such as Lund, Liais and Álvaro da Silveira had made brief remarks about the sinking streams in the area. Lanari, a landowner in the area, described the variation on lake's level and its associated sediments.

Coutard et al.(1978) stated that the groundwater in the area follows both the dip of the limestone and the system of joints. They drew a series of speculative conclusions about the groundwater routes, without performing dye traces. The same authors believed that the lakes' dry periods follow a 15 year cycle. There was no systematic monitoring to support such a statement. The irregular hydrologic pattern of the lakes seems to be more complex.

By mapping the hydrogeology, using aerial photographs and field checking, Silva et al.(1987) determined the hydrogeological domains in the area. Recharge zones occur in the limestone and soil mantle mainly in the karst High Plains. The Mocambeiro Depression and river beds are the main discharge zones.

3.3 Environmental Problems

The large number of cities, villages and farms in and around the area has caused major environmental impact. The Matozinhos-Pedro Leopoldo Karst is one among several regions in Brazil that are undergoing rapid degradation. No remedial plan has been put into effect. In 1990 a significant part of the area was declared a "conservation unity," meaning that further impact must be assessed and controlled. In reality, however, the area continues to be impacted by rapid population growth.

Urbanization is perhaps the greatest cause of environmental problems. Most cities are experiencing an uncontrolled growth. The proximity to the large metropolis of Belo Horizonte makes the area a convenient place for both industries and weekend resorts. Cities like Matozinhos are expanding directly over karstified surfaces. Some streets go across sinkhole bottoms, and limestone cliffs and lakes are becoming enclosed by new urban sites. Groundwater pollution, alteration of the landscape and cave vandalism are byproducts of the urbanization.

Agriculture and cattle farming during the past 200 years have destroyed most of the original vegetation. Soil erosion is becoming a major concern. Furthermore, some large scale projects, such as the building of an international airport, have changed dramatically the landscape and altered the hydrologic regime of nearby lakes. Ground subsidence in urban areas due to groundwater overpumping is a problem of increasing concern. The largest sinkhole collapses have occurred in farmlands so far. However, north of the area, large induced sinkholes have collapsed inside urban limits.

Limestone mining is present throughout the area. Significant caves have been destroyed. Other problems caused by mining are the improper disposal of residue, air and water pollution, and landscape degradation. Only recently, the mining companies have been requested to present a plan of remedial action prior to the beginning of operation.

Groundwater pollution poses a major threat to the hydrologic resources in the region. Pessoa (1992), in a study of a larger area, estimated that approximately 80% of the population relies on groundwater. According to this author, there are three main sources of groundwater pollution in the region: urban activities which cause pollution especially from sewage and landfills, industrial activities that frequently cause pollution by disposing their residue without planning and farming which causes pollution through the improper use of fertilizers. Microbiological contamination has been detected in some selected points in the recharge zone (BMA, 1992).

CHAPTER 4 WATER TRACING

Groudwater tracing is a very useful technique for determining the routes of subsurface flow. A number of tracers may be used. Aley and Fletcher (1976) and Gospodarič and Habič (1976) give detailed information on methods and practical problems associated with the many types of tracers. Dye tracers are among the most common and easy to handle. They have been used extensively in karst terrains all over the world. In Brazil, only isolated experiments have been made, usually for caving purposes. In the Matozinhos-Pedro Leopoldo Karst, the use of dye tracers has been advocated by early cavers (Dequech, 1975). The large number of swallets and springs have led people to speculate on the probable groundwater flow routes, based on the appearance of sugar cane and other vegetal debris supposedly cultivated on the surroundings of certain sinking streams. In fact, some long time residents in the area, after observing the experiments with fluorescein performed for this thesis, remembered seeing some of the streams turn bright green 30 to 40 years ago. The results of these possible dye tracing experiments were not published.

Seventeen qualitative and two quantitative dye tracing experiments were performed in the area.

4.1 Methods

The first step consisted of performing a thorough hydrogeological inventory of the area. All detected karst features with flowing water were marked on a map and described. The discharge of the springs was measured with a current meter. A map of karst landforms by Kohler et al.(1978) at a 1:50,000 scale was taken as a starting basis. The prospected hydrogeological features were marked on 1:10,000 orthogonal aerial photographs and then transfered to a 1:25,000 topographic base map. Some springs issuing from phyllitic rocks were not considered. Only the landforms developed in limestone were taken into account. During the wet periods, several periodic springs appear in the area. Since most of these hydrological features last for only a short period, most of them were not included in the dye tracing experiments. There are also some small springs issuing from soil along the banks of the major streams, such as Mata Creek and Velhas River. These springs, together with other very small karst springs, were not included in the experiments. Figure 4.1 locates the detected groundwater outlets in the area. In this figure, karst windows were omitted and only springs that represent definite outlets for karst basins and subbasins are shown.

Fluorescein and optical brightener were the two dyes chosen for this study. Mull et al.(1988) provided a good summary about the use of these dyes. Optical brightener proved

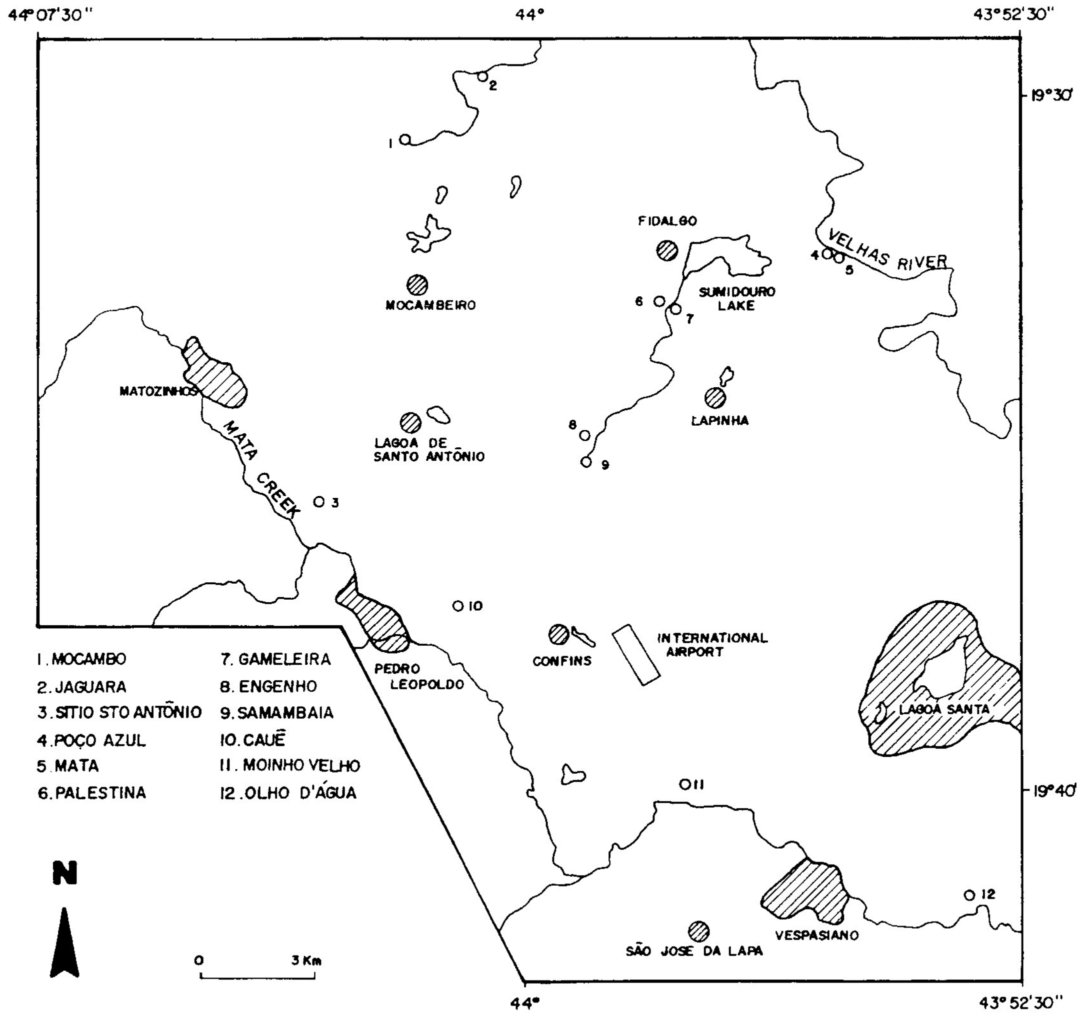


Figure 4.1 Location of Detected Outlets in the Area

to be ineffective as a dye tracer in the area. The possible causes will be discussed in section 4.3. Prior to the experiments, a background test was performed. Receptors for fluorescein and optical brightener were placed in the two most important drainage basins. They were left in the water for one week and then analyzed for dye. The results were negative. There are no significant background levels of fluorescein and brightener in the area.

The basic tracing procedure consisted of injecting a selected quantity of dye at the input point, usually a swallet or karst window. The amount of dye injected was calculated in relation to the distance to the possible output. One-to-five pounds per straight mile were used for fluorescein. For optical brightener two pounds per straight mile were injected.

Passive dye receptors were placed in the possible springs. For fluorescein, the receptor consisted of a small packet of activated charcoal suspended into the water flow by a small diameter nylon rope. The dye is adsorbed onto the activated charcoal as it passes through the receptor. Usually more than one packet was used per spring in a attempt to avoid disturbance and theft by locals. The receptors were collected on average after one week and analyzed for dye. The analysis consisted in placing an amount of charcoal into a small jar and covering it with an eluent solution. The procedure for preparing the eluent consisted in filling a graduated cylinder to the 5 ml mark with solid KOH, covering it with water to the 30 ml mark and adding 70 ml of isopropyl alcohol. The less dense portion of the liquid is added to the jar containing the charcoal. If fluorescein is present the liquid will turn green. Very weak positive tests can be observed through a light beam. The jars were labeled and stored for about a month.

For optical brightener, a small piece of undyed surgical cotton was tied to the same line, together with the charcoal packet. After collecting, the cotton was placed into a homemade wood case containing an ultraviolet light. In a positive test the cotton will fluoresce blue-white.

4.2 Dye Tracing Results

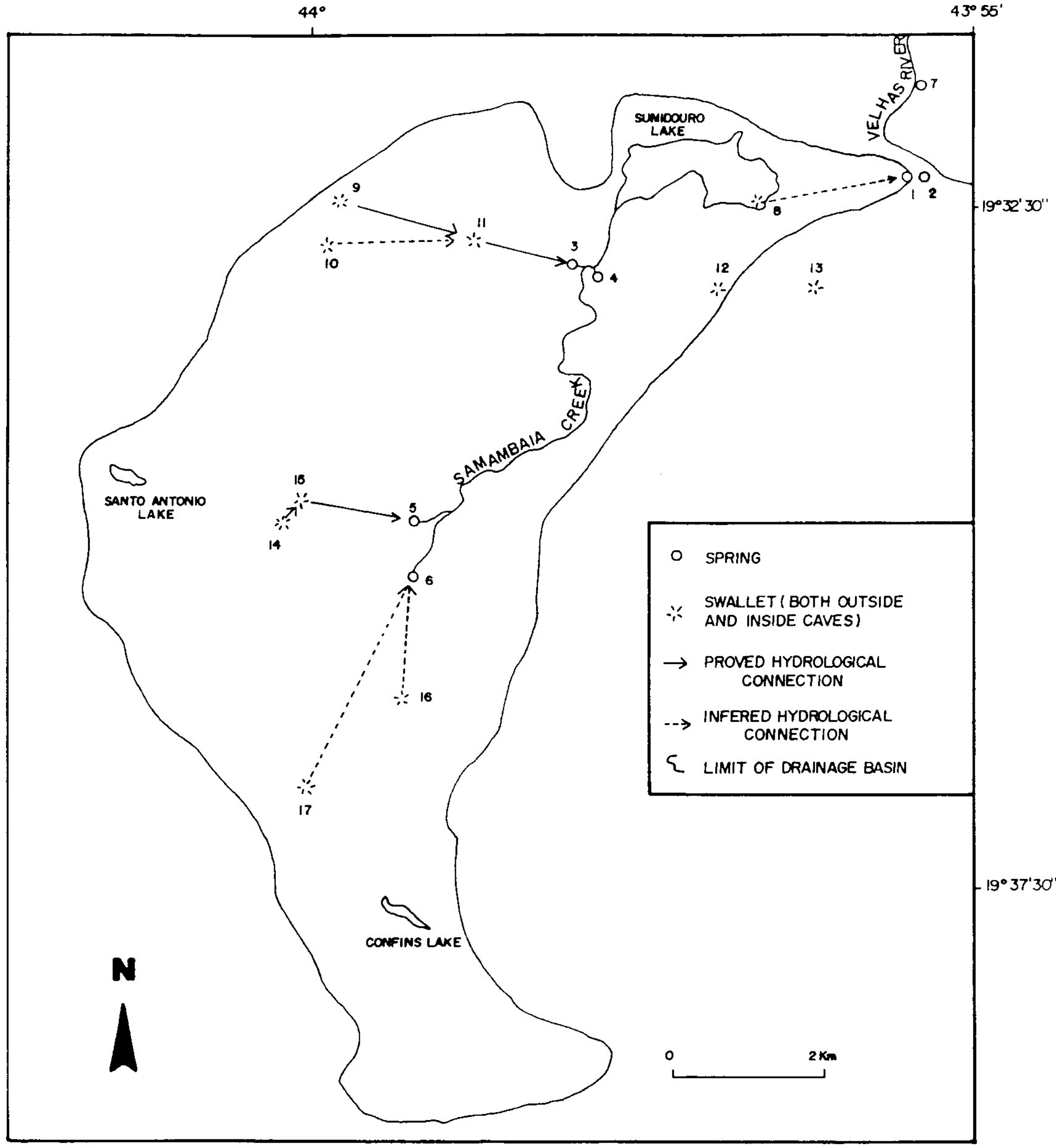
The two major hydrological networks in the area are represented by Samambaia and Palmeiras-Mocambo Creeks. Most of the dye tracing was performed within these basins. Other isolated drainage basins were analyzed also. The discharge values inside brackets correspond to measurements in the dry and wet seasons. Appendix B and Table 4.1 list, respectively, the dye traces and the spring's discharge measurements.

SPRING	DRY SEASON m^3/s	WET SEASON m^3/s	DISCHARGE POINT
Samambaia	0.15	0.15	Velhas River
Engenho	0.05	0.15	Velhas River
Palestina	0.05	0.35	Velhas River
Gameleira	0.05	0.05	Velhas River
Poço Azul	0.15	0.25	Velhas River
Lagoa da Mata	0.05	0.05	Velhas River
Mocambo	0.45	1.00	Velhas River
Jaguara	0.60	0.80	Velhas River
Moinho Velho	0.15	0.15	Mata Creek
Olho d'Água	0.05	0.10	Mata Creek
Cauê	0.05	0.10	Mata Creek
TOTAL	1.80	3.15	

Table 4.1. Discharge measurements and discharge points of major springs of the Matozinhos-Pedro Leopoldo Karst. Dry season measurements made at October 4-7, 1993, except for Cauê spring (August 4, 1994.) Wet season measurements performed at February 2 and 3 1994.

4.2.1 Samambaia Basin

This drainage with its associated hydrogeological features and groundwater routes is shown in Figure 4.2. Samambaia Creek issues from a spring (0.15 - 0.15 m^3/s) and has a perennial surface flow that discharges into Sumidouro Lake. Six tracing experiments were attempted in this basin.



Springs 1.Poço Azul, 2.Lagoa da Mata, 3.Palestina, 4.Gameleira, 5.Engenho, 6.Samambaia, 7.Jaboticatuba's Olho d'Água

Swallets 8.Sumidouro Lake, 9.Curral Cave, 10.Chácara Sinkhole, 11.Francês Hole, 12.Goiaba Swallet, 13.Baldo Swallet, 14.Água Fria Cave, 15.Cocho d'Água Karst Window, 16.Paredãozão Cave, 17.Lapa Vermelha I Cave

Figure 4.2 Drainage and Hydrogeological Features of Samambaia Basin

On February 15, 1993, 3.5 kg of optical brightener were dumped into Cocho d'Água Karst Window (No. 15 on Figure 4.2), a sinkhole with drainage sumped at both sides. Receptors were placed at Engenho Spring (0.05 - 0.15 m^3/s). Analysis of the receptors showed negative results.

Simultaneously, 700 g of fluorescein were dumped into Água Fria Cave (No. 14 on Figure 4.2), a small cave with a diminutive drainage across its lower level. Receptors were placed at Cocho d'Água Karst Window and at Engenho Spring. The results were positive for both receptors.

On November 24, 1992, 500 g of fluorescein were placed into Francês Hole (No. 11 on Figure 4.2), a vertical cave that intercepts a sumped drainage at the bottom. The dye trace was positive on receptors placed at Palestina Springs (0.05 - 0.35 m^3/s).

On November 25, 1992, 500 g of fluorescein were dumped into Curral Cave (No. 9 on Figure 4.2), a small cave with a trickle of water flowing through it. The dye trace was weakly positive on receptors placed into Francês Hole.

On December 5, 1991, 1 kg of fluorescein was dumped into the Baldo Swallet (No. 13 on Figure 4.2). Receptors were placed into Poço Azul Spring (0.15 - 0.25 m^3/s), at Lagoa da Mata Spring (0.05 - 0.05 m^3/s), a crystal clear small spring issuing from a lake, and at Jaboticatuba's Olho d'Água, a hardly noticeable spring at the right bank of Velhas River.

Receptors at Poço Azul and Lagoa da Mata were negative. The receptors at Jaboticatuba's Olho d'Água were stolen.

On December 5, 1991, 3.5 kg of optical brightener were placed near the suspected sinking point of Sumidouro Lake (No. 8 on Figure 4.2). Receptors were placed in Poço Azul Spring, Lagoa da Mata Spring and Jaboticatuba's Olho d'Água Spring. The results were negative at Poço Azul and Lagoa da Mata. Jaboticatuba's Olho d'Água receptors were stolen.

4.2.1.1 Summary

The major part of the water that issues at Samambaia Spring probably comes from Lapa Vermelha I Cave. This cave has a lake in its main passage. During exceptionally dry years, the lake's level drops considerably, showing a good-sized underground creek that appears from a breakdown in its eastern wall and sumps at the end of the cave. This water possibly originates from the area around Confins and Lagoa Bonita Lakes. No dye tracing was attempted due to persistent high water levels during 1991-1993. The trickle of water that sinks at Paredãozão Cave probably also drains to Samambaia Spring.

Engenho Spring drains an area with few identified groundwater features. The water that runs through Água Fria Cave passes through Cocho d'Água Karst Window and eventually appears at Engenho Spring. The several sinkholes to the west of Cocho d'Água and Água Fria probably also drain into this spring.

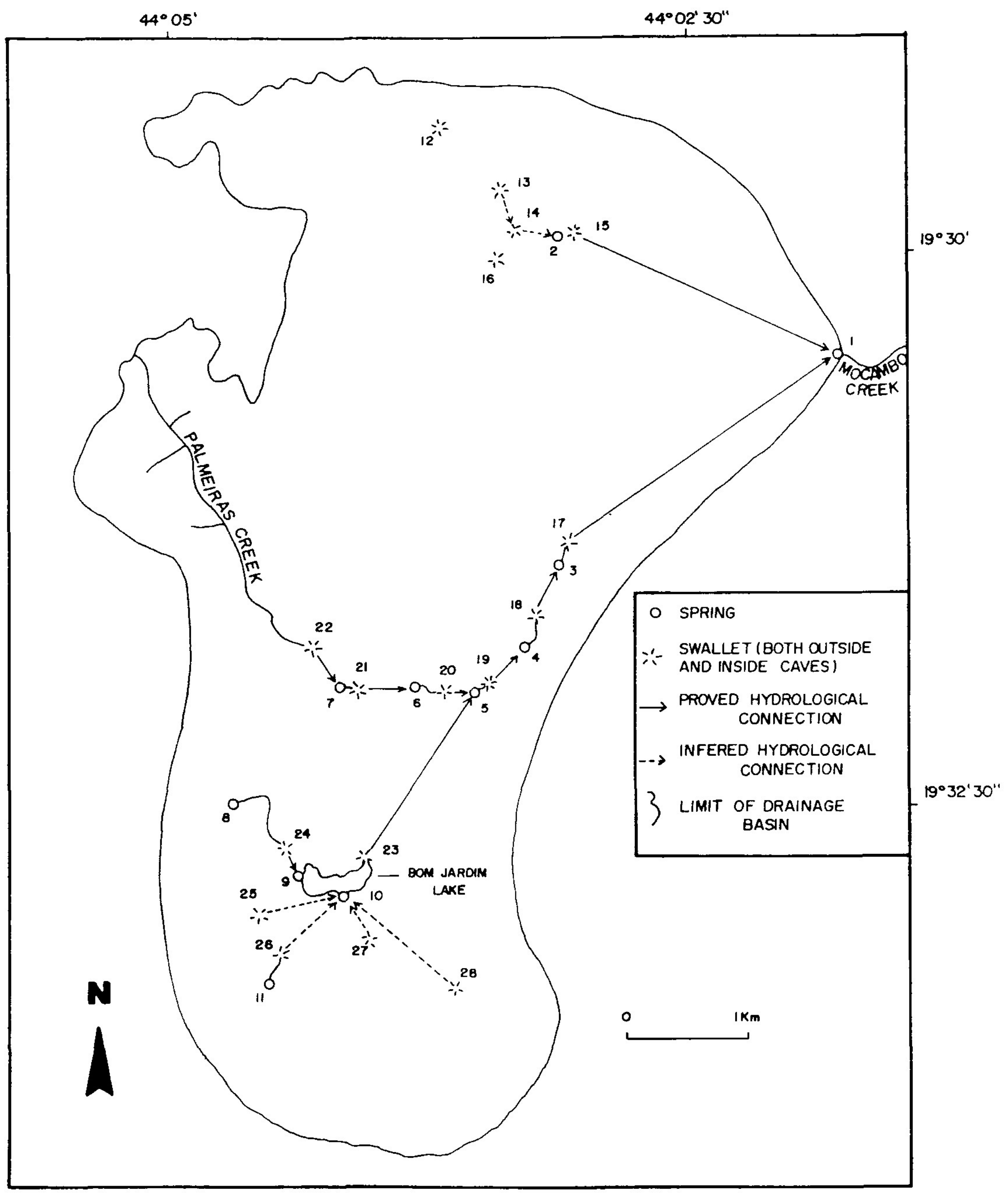
Palestina Spring issues from another large karst basin. The water at Curral Cave drains into Francês Hole and then toward Palestina Spring. Chácara Doline contains the other known hydrogeological feature in this area, a small trickle of water. It probably contributes to the water at Francês Hole. There is also a seepage spring near Palestina, flowing out of soil.

Gameleira Spring (0.05 - 0.05 m^3/s), at the right margin of Samambaia Creek, is the probable outlet of the karst area of Lapinha, to the east. No significant hydrogeological features are known in this area. The small swallet of Goiaba (No. 12 on Figure 4.2) is related either to this spring or to Poço Azul and Lagoa da Mata Springs. Gameleira Spring is located under a small outcrop of limestone. An artificial channel at a terrace directly above the spring drains part of Samambaia Creek. Some of the Gameleira Spring water might originate from infiltrations from this channel.

The origin of the water that flows from Poço Azul Spring, Lagoa da Mata Spring and Jaboticatuba's Olho d'Água Spring could not be identified by tracing. Although the results were negative, Poço Azul is probably the discharge point of the water at Sumidouro Lake due to its proximity and downgradient location. The vast lake volume causes dilution of any dye tracer and prevents the precise location of the swallet. The inlet of Baldo is probably related to Poço Azul or drains to some unrecorded spring over the Velhas River channel. The large amount of sediment that covered the receptor at Poço Azul might have masked the results. The limpid water of Lagoa da Mata does not show discharge variation during the year and probably therefore represents the outlet of a diffuse aquifer. Jaboticatuba's Olho d'Água Spring is considered by many as the outlet of Sumidouro Lake water (Coutard et al., 1978). The receptors placed at this site were stolen. It seems unlikely that a karst conduit would drain under the large and deep channel of Velhas River (average discharge of 85 m^3/s). The volume of water at Jaboticatuba's Olho d'Água is also much smaller than the volume that feeds Sumidouro Lake. Olho d'Água should be one of the outlets of the incipient karst of the right margin of Velhas River.

4.2.2 Palmeiras-Mocambo Basin

Palmeiras-Mocambo Creek drains the Karst High Plain northwest from Samambaia Basin. Figure 4.3 shows the groundwater routes and associated features. Eight dye traces were performed in this basin.



Springs 1.Mocambo, 2.Zé Irene, 3.Poções, 4.Poções Cave, 5.Ballet, 6.Sacota, 7.Milagres, 8.Perobas, 9.Debris, 10.Bom Jardim, 11.Água de Matozinhos

Swallets 12.Foto Aérea Cave, 13.Água Surda Karst Window, 14.Água Surda Cave, 15.Zé Irene, 16.Freática Cave, 17.Poções, 18.Poções Cave, 19.Ballet, 20.Sacota, 21.Milagres, 22.Palmeiras, 23.Bom Jardim, 24.Captação, 25.Faustina, 26.Água de Matozinhos, 27.Boca, 28.Bomba Cave

Figure 4.3 Groundwater Routes and Hydrogeological Features of Palmeiras-Mocambo Basin

On April 1, 1992, 800 g of fluorescein were dumped into the Palmeiras Swallet (No. 22 on Figure 4.3), a small sumped cave. Receptors were placed at Milagres Sinkhole, Sacota Sinkhole and Ballet Sinkhole, all three are large dolines with drainage running through their bottoms. The Milagres and Sacota receptors were positive. The Ballet receptors were negative.

On June 30, 1992, 2 kg of optical brightener were placed into Sacota Sinkhole (No. 20 on Figure 4.3). Receptors were placed into Ballet Sinkhole, Poções Swallet, a spring that drains shortly afterward into a rounded sinking lake, and at Mocambo Spring (0.45 - 1.00 m^3/s). The receptors at Ballet were removed prior to the retrieval. The others gave negative results.

On December 5, 1991, 1.7 kg of optical brightener was dumped at Poções Swallet (No. 17 on Figure 4.3). Receptors were placed at Mocambo Spring and at Jaguara Spring (0.60 - 0.80 m^3/s). Results were negative for both receptors.

On July 27, 1992, 2.5 kg of fluorescein were injected at Sacota Sinkhole. Receptors were placed at Ballet Sinkhole, Poções Swallet, Mocambo Spring and at a karst window between Poções Swallet and Ballet Sinkhole. Positive results were obtained for all receptors.

On November 10, 1991, 1.5 kg of fluorescein was placed into Morro Redondo Cave, a vertical cave that contains a small creek. Receptors were placed at Mocambo Spring and Jaguara Spring. Negative results were obtained for both receptors.

On June 30, 1992, 2.5 kg of fluorescein were injected at Bom Jardim Swallet. Receptors were placed at Sacota Sinkhole, Ballet Sinkhole, Poções Swallet and Mocambo Spring. The receptor at Sacota Spring gave negative results. All others were positive.

On July 30, 1992, 300 g of fluorescein were injected into Captação Swallet (No. 24 on Figure 4.3). Three receptors were placed at small springs at the base of a debris cone on Bom Jardim Lake. The dye was observed coming out after about 39 minutes. The distance between these points is 200 m. The mean velocity was 5.1 m/min.

On May 12, 1993, 2 kg of fluorescein were placed at Zé Irene Sinkhole (No. 15 on Figure 4.3), a karst window. Receptors were placed at Mocambo and Jaguara Springs. Mocambo Spring gave positive results. The Jaguara receptors were negative. The dye came out at Mocambo Spring approximately 14 hours after being injected. The distance covered by the dye is 2,425 m in a straight line. The mean velocity was 3.0 m/min.

4.2.2.1 Summary

Part of the water that sinks at Palmeiras Swallet has its headwaters at the phyllite at the northwestern boundary of the area. This creek has a series of short underground sections in its upper portion. It runs through Milagres Sinkhole, by Sacota Sinkhole, by Ballet Sinkhole, through a series of karst windows, and eventually drains into Poções Swallet. After about 2.5 km it emerges at Mocambo Spring. The negative result on the receptor placed at Ballet Sinkhole during the first dye trace is attributed to the removal of the detector prior to the passage of the dye.

The large swallet at Bom Jardim is fed by two sources. Part of the water comes from Captação Swallet. This swallet drains water from two small creeks, one coming from Perobas Cave. The other source of water comes from Bom Jardim Cave. The drainage area of this resurgence is probably related to a series of small convergent swallets, some associated with the Matozinhos urban area. The water sinking at Bom Jardim Swallet joins the water coming from Palmeiras Swallet between Sacota and Ballet Sinkholes, going toward Mocambo Springs, through an underground route already supposed by the locals in the beginning of the century (SEE, 1938), and hypothesized by Coutard et al. (1978).

The water at Zé Irene Karst Window also drains toward Mocambo Spring. This water is probably related to Água Surda Cave creek and another small karst window to the west. Two other intermittent swallets in the area may also contribute to this drainage.

The dye tracing of the small creek that sumps at the bottom of Morro Redondo Cave gave negative results both to Mocambo and Jaguara Springs. The very small discharge of the creek may have prevented the dye from traveling the long distance (in excess of 3 km) to the presumed resurgence. On the other hand, during the end of the dry season, it was observed that Caetano Lake at Mocambeiro Depression is in fact two lakes -- one working as a spring that drains into the other, a swallet. Perhaps this water is connected to Morro Redondo Creek. Unfortunately, the morphology of Caetano Lake is not favorable for a dye trace, because of dilution in both inlet and outlet lakes. An exceptionally dry season may prove adequate for an experiment.

Jaguara Spring, a major spring in the karst area, is not related to any of the traced swallets. Its drainage basin lies outside the limits of the study area.

4.2.3 Other Sites

4.2.3.1 Moinho Velho Spring

Moinho Velho Spring (0.15 - 0.15 m^3/s) is located in the southern limit of the area (No. 11 on Figure 4.1) and drains into Mata Creek. The sole hydrogeological feature identified nearby is the small creek draining Moinho Cave. Two dye traces were attempted in this site.

On February 16, 1992, 250 g of fluorescein were injected at the downstream end of Moinho Cave. Receptors were placed at Moinho Velho Spring. The result was negative.

In another attempt on May 5, 1993, 210 g of fluorescein were dumped again at the downstream sump of Moinho Cave. Receptors were placed in four sites along the course of Moinho Velho Creek, from the spring to the confluence with Mata Creek. All four were negative.

Clearly Moinho Cave drainage does not flow toward Moinho Velho Spring, or to any unrecorded spring along Moinho Velho Creek. It is hypothesized that this water may drain directly toward Mata Creek.

4.2.3.2 Cauê Spring

Cauê Spring (0.05 - 0.10 m^3/s) was located late during the field work (No. 10 on Figure 4.1). It drains a small area of limestone outcrops heavily modified by mining. No swallets were observed in the area. The spring issues from two separate outlets, draining toward Mata Creek.

4.2.3.3 Olho d'Água Spring

Olho d'Água is the southernmost spring in the area (No. 12 on Figure 4.1), draining toward Mata Creek. No other nearby hydrogeological features were located. Olho d'Água Spring (0.05 - 0.10 m^3/s) may have a hydrological connection with the karst area around Lagoa Santa's Lapa Vermelha, a mined limestone outcrop.

4.3 Discussion

The high number of negative results was caused by at least two factors. The experiments with optical brightener were highly unsuccessful. The poor performance is probably related to bad quality (or improper composition) of the Brazilian brightener used. Although the dye performed well in some laboratory experiments (e.g. pouring small quantities of dye into a water container), in the field it proved to be ineffective. Even large amounts of dye were not sufficient. The use of optical brightener in other tropical areas has shown that large losses can occur due perhaps to adsorption or photochemical decay (Smart and Smith, 1976).

Fluorescein dye performed better, but its use in the Matozinhos-Pedro Leopoldo Karst proved to be less effective than in temperate regions. Smart and Smith (1976) stated that fluorometric dye tracing in tropical areas using charcoal receptors is not recommended due to its poor performance. To overcome this difficulty, much larger quantities of fluorescein were used. Most of the analyzed activated charcoal receptors were only weakly positive.

Another drawback of standard dye tracing techniques in the Matozinhos-Pedro Leopoldo Karst arises from the fact that some swallets and springs are lakes during most of the year. Sites such as Sumidouro Lake would require very large amounts of dye to achieve positive results. Not enough dye was available for such experiments. Better results would be obtained in exceptionally dry years when the swallets are revealed in the lake bed, allowing the dye to be injected without being diluted. Such dry periods are reported to occur at approximately 5-to-10 year intervals. The last one was probably during 1988. On such occasions, a straightforward dye trace could be attempted.

The karst recharge water is predominantly autogenic. Very little water comes from other lithologies. The water is collected by infiltration via small swallets and sinkholes. The Velhas River is the major discharge zone of the karst water. The observed total discharge of the springs totals approximately 1.80 m^3/s during the dry season and 3.15 m^3/s during the wet season. The sum of the discharge of the springs that drain toward Velhas River account for 88% of the total volume. The remaining 12% flows to Mata Creek (see Table 4.1). Groundwater flow was considered to be influenced by fractures by Silva et al. (1987) and by both fractures and dip by Coutard et al. (1978). These factors appear to exert a visible control over groundwater flow, especially considering that the geologic dip is generally toward Velhas River and that prominent jointing also extends in this direction. However, some flow routes do not follow these structures. The favorable drainage routes toward Velhas River reflect both the geologic structure and the availability of limestone in this direction, since the western and southern limits of the area are composed of gneiss. Most of Mata Creek margins are bounded by gneiss. The three springs that flow toward Mata Creek are enclosed in karst areas surrounded by impermeable lithologies (phyllite and gneiss). It is likely that other small, unrecorded springs exist in the area.

Samambaia Creek provides a local base level in the southeastern Karst High Plain. Much of the incoming flow is concentrated in four springs along its margin. In this area, the general flow pattern of the underground tributaries is not directed toward Velhas River, but toward Samambaia Creek. However, in the Palmeiras-Mocambo Basin, groundwater flow is more straightforward, not dispersing much from the general trend toward Velhas River. The controlling factor for groundwater flow in the Samambaia Basin appears to be the position of the nearest significant base level river. Existing sets of joints can be used for groundwater flow, according to the direction of the hydraulic gradient.

The sum of the volume of all springs that drain into Samambaia Creek is about twice the discharge of Poço Azul Spring, the presumed resurgence of the system. A significant amount of water is pumped and diverted from Samambaia Creek in its 8 km long surface run to Sumidouro Lake. Part of this water may be lost by evapotranspiration, after agricultural and domestic use. The large surface area of Sumidouro Lake may also cause significant evaporation losses. It is also possible that Poço Azul Spring is not the sole outlet of Sumidouro Lake.

Some springs do not represent the discharge zone of any traced route. They usually have crystal clear water year-round and show slow response to rainfall. This is the case of Jaguara, Moinho Velho and Lagoa da Mata Springs. These outlets may be the discharge points of a distinct aquifer, possibly a diffuse flow aquifer. The behavior of these springs will be further analyzed in the next chapter. The other springs show rapid response to rainfall and have turbid water during the wet season. Most of them have been connected to swallets or karst windows by dye tracing. The turbid water may be related to turbulent conduit flow with open channel and/or surface sections. Springs such as Olho d'Água and Gameleira, although not as yet connected by dye traces to any water inlet, probably carry water from undiscovered caves.

The results obtained in the quantitative dye trace of Zé Irene-Mocambo is typical of karst water (Smith et al., 1976; Milanovic, 1981). The experiment in Captação Swallet is unreliable in this respect because a huge pile of debris, released by a nearby mining company over the traced route, has altered the flow behavior. Water speed at the upstream section of the drainage basins is likely to be higher due to steeper hydraulic gradients, open channel conditions and occurrence of collapsed features with aerial fluvial sections. The Mocambeiro Depression has a much gentler hydraulic gradient, causing groundwater flow to be slower, probably through completely submerged channels.

4.4 Delineation of Drainage Basins

The determination of groundwater divides in karst terrain poses a number of problems. Groundwater in karst may flow beneath topographic divides. Most of the time the divide must be inferred because it is rarely directly observed. Detailed water tracing and the making of a potentiometric map are good ways to increase the accuracy of the estimated divides.

Using the groundwater flow routes, the major drainage basins were delineated (Figure 4.4). This map should be considered as a very first attempt to draw the different groundwater basins in the area. Moinho Velho, Olho d'Água and Cauê Drainage Basins were determined without the aid of dye traces. The estimated limits in these cases must be considered as tentative. Runoff directions in surface landforms and lithological contacts were used in estimating the basins' limits.

Phyllite deposits cover limited portions of the area, resulting in a local predominance of surface flow. Semiconfined flow may occur then. Surface drainage basins were not delineated on the map. Table 4.2 gives the approximate area of the karst drainage basins, measured with a Keuffel & Esser compensating polar planimeter on a 1:25,000 base map. Other undetected drainage basins exist, such as the one that drains to Caetano Spring. These basins were not taken into account due to the limited data available.

	Samambaia	Palmeiras-Mocambo	Moinho Velho	Cauê	Olho d'Água
Area	70	30	4	3	3

Table 4.2 Approximate size of the delineated groundwater drainage basins. Area in km^2.

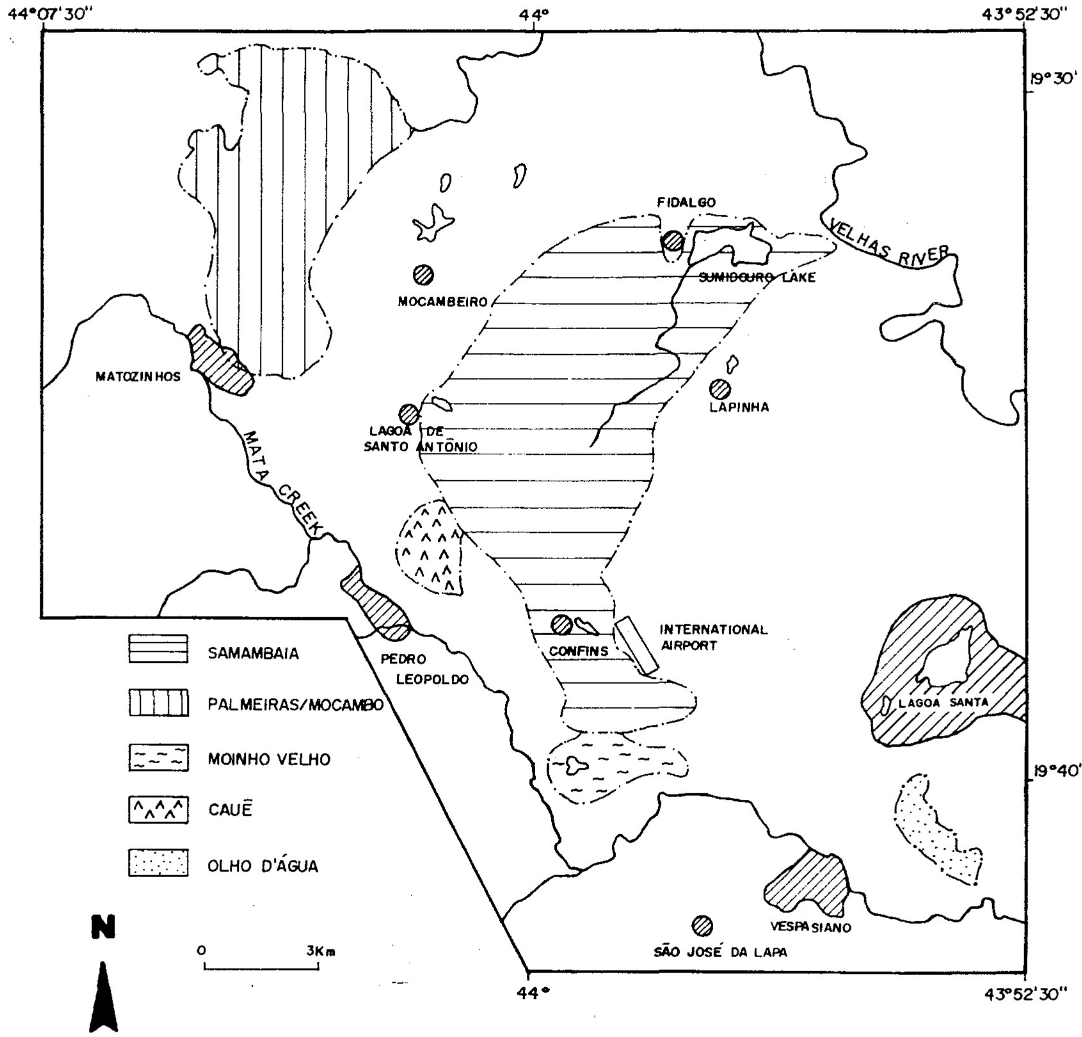


Figure 4.4 Drainage Basins at the Area

4.5 Conclusions

The water drained by the Matozinhos-Pedro Leopoldo Karst is almost entirely autogenic, originating from runoff into the limestone.

About 88% of the identified discharge drains toward Velhas River, the regional base level. Twelve percent drains to Mata Creek. Samambaia Creek is a local base level, concentrating a series of springs along its channel.

A large number of unsuccesful dye traces are attributed to the poor performance of optical brightener, fluorescein and the related receptors under tropical conditions.

Five distinct drainage basins were delineated in the study area. Other basins may exist, especially in the Mocambeiro Depression. The flow in the upstream portion of the area tends to be turbulent and possibly vadose. Phreatic flow dominates the lower hydraulic gradient downstream portion.

CHAPTER 5 HYDROCHEMISTRY

No significant published data are available about the chemical characteristics of karst water in the Matozinhos-Pedro Leopoldo area. Only a few analyses have been performed by previous researchers. The goal of the hydrochemical survey of the karst water is to provide a first insight into the basic composition of the water and its seasonal variations. The nearby urban areas and industries are possible sources of groundwater contamination. Water quality was established at selected points. The hydrochemical data are also useful as a means to compare and distinguish different types of springs. The variation of chemical parameters with time can help to characterize the type of flow (Shuster and White, 1971).

The denudation rates were also calculated. These data provide a chemical basis from which some assumptions about karst evolution can be drawn.

5.1 Methods

Eleven physical and chemical parameters were measured in four different sites in order to characterize the water chemistry. Temperature was measured in the field using the temperature probe of the portable Fisher Accumet Mini pH Meter, model 955. Measurements of pH were also done in the field with the same equipment. Specific conductance readings were taken in the field with a Fisher Conductivity Meter.

The selected chemical parameters were calcium, magnesium, alkalinity, chloride, potassium, sodium, sulfate and nitrate. The collected samples were stored in a cooler before being transported to Belo Horizonte. Two different laboratories (Ecolab and Sanear) performed the measurements. All samples for cations were acidified (to pH<2) with HNO_3. Calcium and magnesium were measured by titration with EDTA. Potassium was measured with a Hach DR/2000 spectrophotometer. Sodium was determined by atomic absorption using a Variantechtron instrument. Chloride was determined by volumetric methods. Sulfate was measured by turbidimetry using a Polilab AP 1000 Turbidimeter. Nitrate was acidified (to pH<2) with H_2SO_4 and determined by spectrophotometric method using a Shimadzu Spectrophotometer. Due to the low values of the chemical parameters other than calcium, magnesium and alkalinity, the lower limit of detection was considered as being 1 mg/l. The range in values below this limit were not taken in account in the statistical calculations.

5.2 Sampling Points

Sampling locations were selected at sites that would represent the downstream end of a groundwater flow path as it emerges from the subsurface. Four springs were selected. They are among the largest in the area: Moinho Velho Spring, Mocambo Spring, Jaguara Spring and Poço Azul Spring. These four sites represent more than 90% of all detected outlet flow. Additional sampling was made at Cauê Spring and Olho d'Água Spring. Figure 5.1 shows the location of the sampling points.

5.3 Sampling Events

Monthly sampling was planned at the beginning of the project. However, pH meter breakdown, impassable roads during the wet season and other problems prevented monthly sampling. Event sampling was then chosen as an alternative approach. Nine sampling events were selected as follows:

October 17, 1991. End of the dry season. After a short duration rain.

November 26, 1991. End of the dry season.

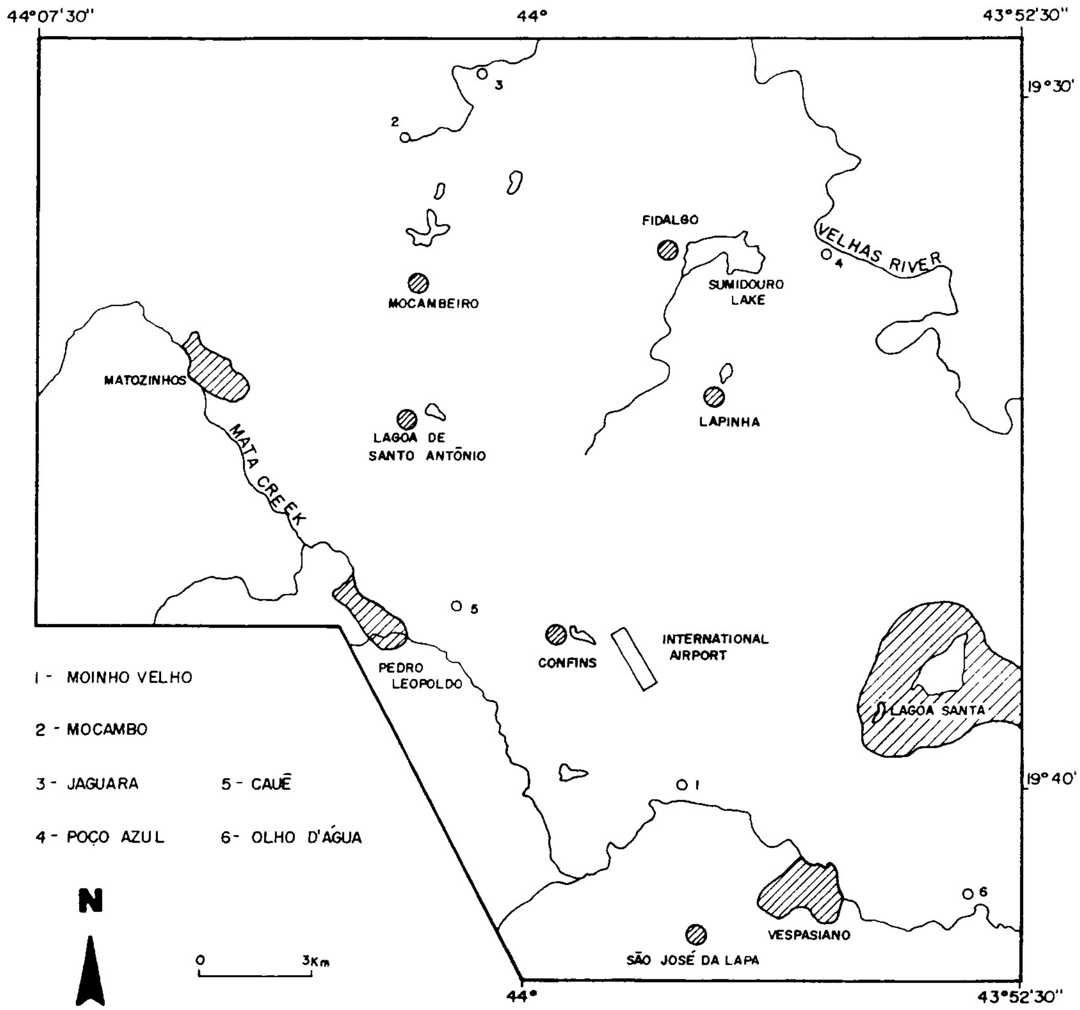


Figure 5.1 Location of Sampled Springs

December 19, 1991. Beginning of the wet season. Only temperature, conductivity and pH were measured.

June 4, 1992. Middle of the dry season.

July 9, 1992. Middle of the dry season.

March 1, 1993. End of the wet season.

October 4-7, 1993. End of the dry season. Soon after a short duration storm.

February 2, 1994. Middle of the wet season.

August 4, 1994. Middle of the dry season.

5.4 Results

5.4.1 Physical and Chemical Parameters

The assemblage of results gives a good insight on the chemical characteristics of the karst water. Each parameter will be discussed separately.

5.4.1.1 Temperature

Table 5.1 gives the results of temperature measurements. Moinho Velho and Jaguara Springs have the smallest temperature ranges throughout the year, both around 0.5°C. Mocambo Spring, the outlet of a drainage with many surface sections, has a much higher variation (2.0°C). The water at Poço Azul Spring comes out as a small lake, subject to insolation. This spring probably drains the large Sumidouro Lake. The high temperature values at this spring are, therefore, probably due to heat of lake water by sunlight. During the winter, both Poço Azul and Mocambo Springs have a sharp decrease in temperature while the water temperature at Jaguara and Moinho Velho Springs remains nearly constant.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	23.0	22.8	23.0	25.5
11-26-91	23.1	23.0	23.0	26.1
12-19-91	23.4	23.7	23.0	24.5
06-04-92	23.2	22.2	22.8	23.9
07-09-92	22.9	21.9	22.7	23.6
03-01-93	23.0	23.3	23.2	27.3
10-4/7-93	23.1	22.6	22.8	24.3
02-02-94	23.1	23.9	-	24.1

Table 5.1 Temperature values for springs (in °Celsius).

5.4.1.2 Specific Conductance

Table 5.2 provides the specific conductance values taken at the four springs. Jaguara Spring consistently had the highest values. The smallest values were measured at Moinho Velho Spring. Most of the springs show an increase in specific conductance during high discharge. At the December 19 sampling, Moinho Velho, Jaguara and Poço Azul Springs showed an increase in values while the specific conductance at Mocambo Spring decreased a bit.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	308	340	357	328
11-26-91	306	342	360	332
12-19-91	319	339	371	343
06-04-92	301	333	357	328
07-09-92	306	328	355	334
03-01-93	305	340	362	329
10-4/7-93	303	361	386	334
02-02-94	307	355	368	330

Table 5.2 Specific conductance measurements for springs (in micromhos per centimeter at 25°C).

5.4.1.3 pH

The pH measurements were subject to a series of problems related either to equipment breakdown or low quality buffers. The values were highly inconsistent. It was decided to consider them only as approximate values. All pH values fall between 7.10 and 7.87. Jaguara Spring had the highest range while the highest values were taken at Mocambo Spring.

5.4.1.4 Calcium

The calcium values obtained are representative of limestone areas (Table 5.3). The data show an increase during the dry season, followed by dilution during wet periods. Jaguara Spring has the highest mean calcium concentration and Moinho Velho Spring has the smallest. All four springs show a large range of values.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	62.3	70.3	85.8	65.7
11-26-91	150.0	144.0	148.0	158.0
06-04-92	163.3	181.8	193.9	173.7
07-09-92	146.9	179.6	191.8	167.3
03-01-93	60.2	61.8	69.7	58.7
10-4/7-93	50.2	61.2	67.7	62.7
02-02-94	58.5	69.8	71.7	66.0

Table 5.3 Calcium values for springs (in mg/l).

5.4.1.5. Magnesium

Magnesium values are shown in Table 5.4. They follow the trend set by the calcium cation, although the ratio between them (Ca/Mg) varies greatly. Magnesium values exhibit an erratic pattern. Sharp increases were measured in samples taken one month apart (sampling of June 4 and July 9).

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	2.1	1.2	1.0	2.5
11-26-91	10.0	8.0	-	12.0
06-04-92	-	4.0	4.0	12.1
07-09-92	20.4	12.2	6.1	28.6
03-01-93	2.3	5.2	3.1	6.8
10-4/7-93	6.2	3.8	4.8	6.7
02-02-94	2.3	1.1	2.3	1.1

Table 5.4 Magnesium values for springs (in mg/l).

5.4.1.6 Alkalinity

Alkalinity from bicarbonate was the only one considered in this study. Apart from a lack of measurements in the first sampling, alkalinity values increased during high discharge and decreased during low discharge -- an inverse trend compared to the other parameters. The values are shown in Table 5.5. Jaguara Spring had the highest values and Moinho Velho had the smallest.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
11-26-91	165	174	175	176
06-04-92	153	164	178	167
07-09-92	151	162	177	166
03-01-93	160	176	187	175
10-4/7-93	156	168	186	178
02-02-94	157	180	193	172

Table 5.5 Alkalinity values for springs (in mg/l).

5.4.1.7 Chloride

Chloride comes from rainfall, landfills, organic wastes, fertilizers, or may occur naturally in soil. Chloride data are shown in Table 5.6. The karst water does not contain significant amounts of chloride.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
06-04-92	<1.0	<1.0	<1.0	<1.0
07-09-92	<1.0	<1.0	<1.0	<1.0
03-01-93	<1.0	<1.0	<1.0	<1.0
10-4/7-93	<1.0	<1.0	<1.0	<1.0
02-02-94	1.3	1.5	<1.0	<1.0

Table 5.6 Chloride values for springs (in mg/l).

5.4.1.8 Potassium

Most of the measured values for potassium fall below 1 mg/l (Table 5.7).

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	<1.0	<1.0	<1.0	<1.0
11-26-91	<1.0	<1.0	<1.0	<1.0
06-04-92	1.0	<1.0	<1.0	1.0
07-09-92	<1.0	<1.0	<1.0	<1.0
03-01-93	<1.0	<1.0	<1.0	<1.0
10-4/7-93	<1.0	<1.0	<1.0	<1.0
02-02-94	<1.0	1.4	<1.0	1.2

Table 5.7 Potassium values for the springs (in mg/l).

5.4.1.9 Sodium

According to the data shown in Table 5.8, sodium was concentrated during the dry season and at the middle of the wet season. The highest values belong to Poço Azul Spring. Jaguara Spring has the smallest values.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	<1.0	<1.0	<1.0	1.4
11-26-91	<1.0	<1.0	<1.0	1.6
06-04-92	1.5	1.2	1.3	2.0
07-09-92	1.1	1.2	<1.0	1.9
03-01-93	<1.0	1.1	<1.0	1.6
10-4/7-93	<1.0	<1.0	<1.0	1.2
02-02-94	1.2	1.2	1.8	2.8

Table 5.8 Sodium values for springs (in mg/l).

5.4.1.10 Sulfate

Rainfall, bedrock (including pyrite), anaerobic decay of organic material, chemical fertilizers, runoff from livestock feedlocks and sewage effluents are the possible sources of sulfate (Grow, 1986). Low values characterize the sampled water. Mocambo Spring has the highest values. Moinho Velho Spring shows very low levels of sulfate throughout the year. Table 5.9 presents the sulfate values.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	<1.0	5.0	1.3	1.1
11-26-91	<1.0	6.9	1.7	1.2
06-04-92	<1.0	<1.0	<1.0	<1.0
07-09-92	<1.0	<1.0	<1.0	<1.0
03-01-93	<1.0	1.0	<1.0	<1.0
10-4/7-93	<1.0	4.0	1.0	<1.0
02-02-94	<1.0	<1.0	<1.0	<1.0

Table 5.9 Sulfate values for springs (in mg/l).

5.4.1.11. Nitrate

Nitrate comes mainly from agricultural sources, usually associated with fertilizers. Jaguara and Mocambo Springs present the highest nitrate content (Table 5.10). The values do not show an apparent pattern.

	Moinho Velho	Mocambo	Jaguara	Poço Azul
10-17-91	<1.0	<1.0	<1.0	<1.0
11-26-91	<1.0	<1.0	<1.0	<1.0
06-04-92	1.1	<1.0	2.0	<1.0
07-09-92	<1.0	<1.0	<1.0	<1.0
03-01-93	<1.0	1.4	2.0	<1.0
10-4/7-93	<1.0	1.3	<1.0	<1.0
02-02-94	<1.0	1.6	<1.0	<1.0

Table 5.10 Nitrate values for springs (in mg/l).

5.4.1.12 Additional Chemical Data

Some isolated samplings were made at other sites. Olho d'Água spring was located after much of the field work had been done. Three water samples were collected for the purpose of characterizing the major parameters. Table 5.11 shows these data.

	Temp.	SpC	Ca	Mg
10-4-93	22.6	329	64.2	11.4
2-2-94	22.7	353	67.9	2.3
8-4-94	23.1	320	63.1	1.9

Table 5.11 Physical and chemical measurements at Olho d'Água Spring. Temperatures in °C, Specific Conductance in microhmos per centimeter at 25°C, Ca and Mg in mg/l.

Cauê Spring was also found at the final stages of the thesis field work. It drains a heavily mined area. Cauê Spring was sampled for the standard set of parameters (Table 5.12). The spring consists of two outlets: one draining from under a limestone outcrop and the other coming out diffusely at a bog subject to intense sun heat.

	2-2-94	8-4-94
Temperature	23.1	22.3
Sp. Conductance	426	367
Calcium	73.6	72.3
Magnesium	0.7	2.3
Alkalinity	195	182
Chloride	1.8	<1.0
Potassium	<1.0	<1.0
Sodium	2.6	<1.0
Sulfate	<1.0	5.2
Nitrate	4.4	2.7

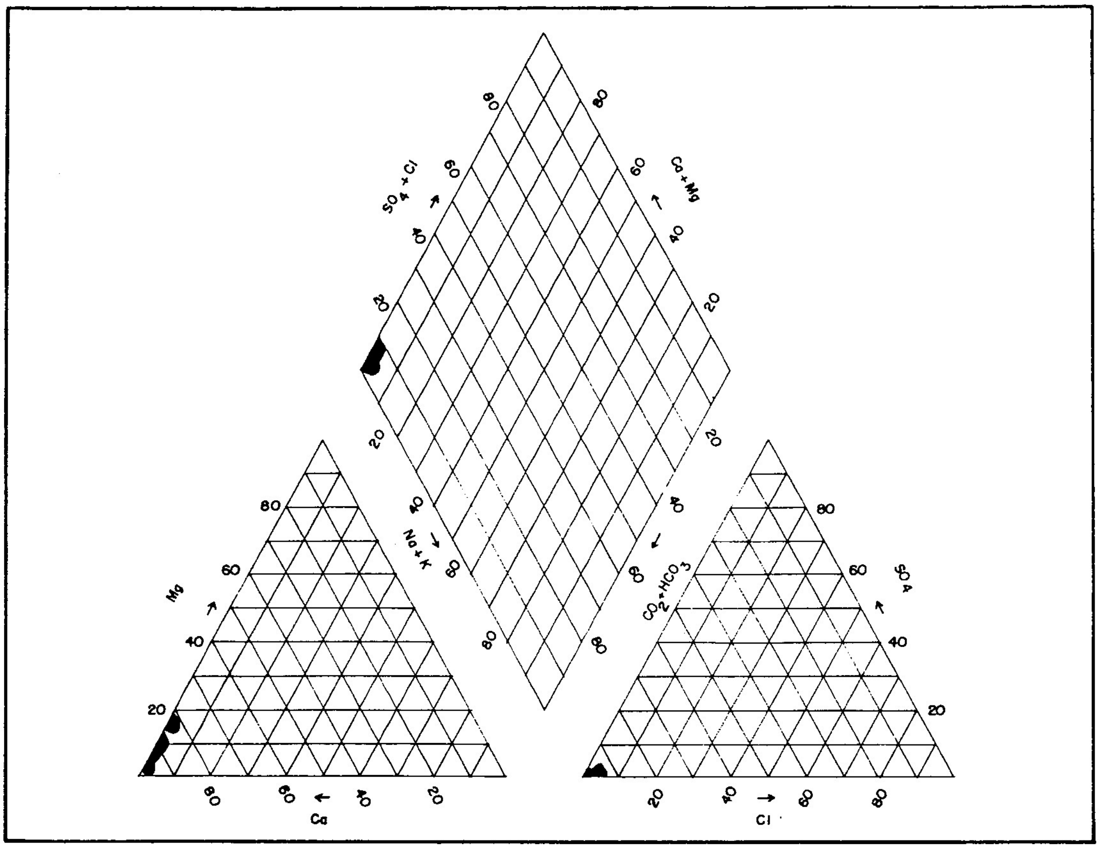
Table 5.12 Physical and chemical data from Cauê Spring. Temperatures in °C, Specific Conductance in microhmos per centimeter at 25°C. Other values in mg/l.

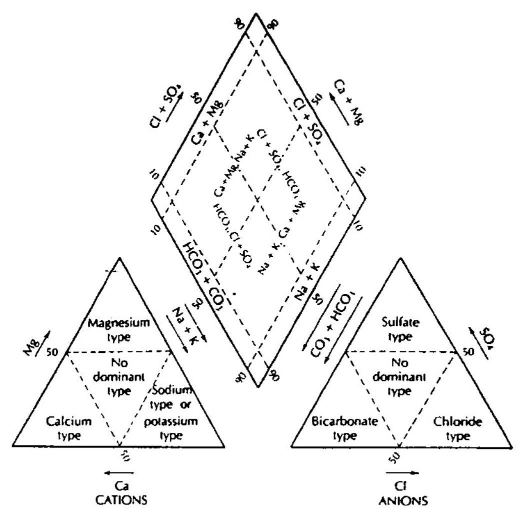
5.5 Discussion

Water chemistry of karst springs is related to discharge, season (Jacobson & Langmuir, 1974), CO_2 supply (Atkinson, 1977), bedrock and surficial geology (Drake, 1983), recharge type and flow path length (Scanlon & Thrailkill, 1987) and human activities. Several studies on hydrochemistry of springs have been performed throughout the temperate world (for example Bakalowicz, 1979 and Patterson, 1979). Very few have taken place in tropical areas, most of them (such as Miller's (1981), Laverty's (1980) and James' (1980) works) gathered data on selected months during expeditionary type research. One of the few comprehensive surveys of groundwater chemistry in tropical karst was made by Crowther (1989) in Malaysia. In his study of autogenic percolation, he attributed the variability in calcium values to different source area PCO_2's and underground reprecipitation of carbonate minerals.

The water type of all four springs falls into a calcium bicarbonate type, according to the trilinear diagram containing all analysis presented (Figure 5.2). The lack of significant concentrations of ions other than calcium and magnesium attest to the autogenic nature of the recharge water.

The effects of increased discharge on the water chemistry of springs are still controversial and depend on the type of flow and behavior of the aquifer. Several studies point out that a dilution occurs as discharge increases (Ogden & Rauch, 1976; Ash & Ehrenzeller, 1983; Meus, 1988; Sesiano, 1989). However, a direct correlation between discharge and chemical parameters has been found in some cases (Rossi, 1976; Crowther, 1989). Complex behavior has been found in some situations (Bakalowicz, 1979; Miller, 1981). Clearly, some ions show distinct response to different flow conditions. Differences in the frequency of sampling especially during the storm flow events can help explain the distinct interpretations.





Hydrochemical Classification System Using the Trilinear Diagram (Fetter, 1988)

Figure 5.2 Trilinear Diagram Showing the Ranges of Values of all Sampled Water

The general trend for the Matozinhos-Pedro Leopoldo Karst is of a dilution of the chemical parameters. Higher values are found during the dry season, related to increased residence time during low discharge. The response times of the springs are diverse due to variations of type and speed of water flow. Springs such as Mocambo show a faster response in the physical and chemical parameters. Table 5.13 summarizes the physical and chemical characteristics of the four monitored springs.

		MOINHO VELHO	MOCAMBO	JAGUARA	POÇO AZUL
T	RANGE	22.9 - 23.4	21.9 - 23.9	22.7 23.2	23.6 - 27.3
	MEAN	23.1	22.9	22.9	24.9
	SD	0.1	0.7	0.2	1.3
	CV	0.6	3.0	1.1	5.1
SpC	RANGE	301 319	328 - 361	355 386	328 - 343
	MEAN	307	342	364	332
	SD	5	11	10	5
	CV	2	3	3	2
Ca	RANGE	50.2 - 163.3	61.2 - 181.8	67.7 193.9	58.7 173.7
	MEAN	98.8	109.8	118.4	107.5
	SD	51.5	56.4	58.0	55.3
	CV	52.12	51.3	49.0	51.5
Mg	RANGE	2.1 - 20.4	1.1 12.2	1.0 - 6.1	1.1 - 28.6
	MEAN	7.2	5.1	3.6	10.0
	SD	7.2	3.9	1.8	9.2
	CV	99.3	77.3	51.1	92.3
ALK.	RANGE	151 - 165	162 - 180	175 - 193	166 - 178
	MEAN	157	171	183	172
	SD	5	7	7	5
	CV	3	4	4	3
Cl	RANGE	<1.0 - 1.3	<1.0 - 1.5	<1.0	<1.0
K	RANGE	<1.0 - 1.0	<1.0 1.4	<1.0	<1.0 - 1.2
Na	RANGE	<1.0 - 1.5	<1.0 - 1.2	<1.0 - 1.8	1.2 - 2.8
SO_4	RANGE	<1.0	<1.0 - 6.9	<1.0 - 1.7	<1.0 - 1.2
NO_3	RANGE	<1.0 - 1.1	<1.0 - 1.6	<1.0 - 2.0	<1.0

Table 5.13 Summary of the physical and chemical parameters of the monitored springs. Range of minimum and maximum values. SD (Standard Deviation). CV (Coefficient of Variation) in percentage. Temperature in °C. Specific conductance in microhmo/cm at 25 °C. Other values in mg/l.

5.5.1. Temperature

Temperature measurements at Jaguara and Moinho Velho Springs show a small coefficient of variation. This is probably related to a flow with no surface connections (closed system). The air temperature variation during the seasons does not affect the water temperature significantly. On the other hand, the variation on temperature values of Mocambo and Poço Azul is typical of an open system. According to Bonacci (1987), waters with great variation of temperature throughout the year generally represent turbulent conduit flow. Diffuse flow shows little variation (Jaguara and Moinho Velho Basins). The marked increase in the values during summer for Mocambo Spring should be credited to both high summer temperatures and small residence time under turbulent conditions, due to the increase in discharge and water velocities.

5.5.2 pH

The unknown accuracy of the pH values obtained precludes any further consideration.

5.5.3 Specific Conductance, Alkalinity and Hardness

The specific conductance is proportional to the total ion concentration in the water. Jaguara and Mocambo have the highest mean values. Moinho Velho has the smallest. These values could be related to drainage basin area or CO_2 availability. The small size of Moinho Velho Basin gives a shorter groundwater path. According to Ogden & Quick (1986), high specific conductance values mean a higher residence time. The shorter groundwater path of Moinho Velho Basin would allow less time for water-rock interactions assuming the flow velocities are similar. The same holds true for alkalinity and hardness. The other three springs are the outlet of much larger drainage basins, therefore possessing higher specific conductance values.

Alkalinity falls in the usual range of karst waters (Milanovic, 1981), being similar to values obtained in Puerto Rico and Jamaica (Corbel & Muxart, 1970). It behaves inversely to the hardness, the highest values occuring during the wet season. Hardness values are inversely related to the discharge. All four springs have a large variation, indicating the effect of recharge water on the aquifer. Scanlon (1989) obtained similar results in Ca-subtype water in the Inner Bluegrass Region of Kentucky. The hardness dilution data do not match the temperature data for Moinho Velho and Jaguara Springs. Probably the aquifer that drains these springs has a small storage capacity, being frequently replenished by runoff water, although the flow is slow enough to allow the temperature to reach equilibrium with the rock. However, although the hardness undergoes dilution during the wet season, the discharge at Moinho Velho Spring was constant during both seasons. This curious behavior of Moinho Velho Spring could be related to the storage characteristics of this aquifer, holding the incoming recharge water and supplying it to the spring at a constant rate. The dilution, however, would occur due to the mixing with the unsaturated recharge water. More sampling and discharge measurements are needed to provide a better understanding of the dynamics of this drainage basin. Jaguara Spring has the highest mineralization. Moinho Velho has the smallest values. Magnesium values experience sharp variations throughout the year.

According to White (1990), PCO_2 in the soil of warm climate regions is maximized in the wet season. The significant increase in hardness values soon after the wet season could be attributed not only to the decrease in discharge but also to the increased availability of CO_2 in the soil due to plant growth during the wet season. The decrease in hardness values for all springs in two samplings made one month apart in the middle of the dry season can be associated with the lowering levels of biogenic CO_2 caused by the lack of rainfall.

Cauê Spring and Olho d'Água Spring were sampled few times and showed no significant variation between the wet and dry seasons. Their small drainage basins are located near urban areas, and they have been highly modified by mining. Percolation through limestone debris may increase the values of chemical parameters. A more thorough sampling is needed.

5.5.4 Other Parameters

The series of cations and anions analyzed show that contaminant levels at all four springs are within acceptable limits. The maximum levels for Class 1 type water (used for human consumption with little treatment) by the Brazilian government are: 250 mg/l for sulfate and chloride and 10 mg/l for nitrate. The karst water, despite intensive urbanization and agriculture in most of the recharge zones, is remarkably clean. BMA (1992) sampled water in the recharge zone of the Palmeiras-Mocambo Basin. In this study the chemical and microbiological parameters analysed were turbidity, total solids, total dissolved solids, hardness, dissolved oxygen, biochemical oxygen demand, nitrate, phosphate, oil, total coliforms, fecal coliforms and fecal streptococo. High levels of total coliforms (>2,400 per 100 ml) and low levels of dissolved oxygen (minimum of 3.5 mg/l) were found in some selected points. Except for nitrates, the distinct parameters studied by BMA (1992) and this writer preclude an immediate comparison between the water at the recharge and discharge zones. Nitrate levels were comparatively low for both zones.

There is a mixed behavior of the parameters according to discharge. Some may undergo dilution during the wet season, while others may become concentrated in the epikarst and soil and then be washed through during rains, increasing the concentration during the wet season (Quinlan & Alexander, 1987). Poço Azul Spring showed the highest values of sodium, probably related to concentration due to evaporation at Sumidouro Lake as well as in other reservoirs along Samambaia Creek. As expected, the highest levels of sulfate were found at the Mocambo Spring due to the fact that it drains water that comes both from the city of Matozinhos and from a large cement industry. The values at Mocambo Spring are at least three times higher than those of the other monitored springs. Jaguara Spring on the other hand, has some of the lowest values in sulfate, potassium, sodium and chloride. However, the values of nitrate at Jaguara Spring, although quite low, remain the highest among the springs, because its catchment area, although away from urban centers, has several farms with intensive agriculture. Mocambo Spring also shows increase in nitrate levels during the wet season, probably related to the harvesting cycle.

Cauê and Olho d'Água Springs need additional data. These springs drain heavily mined areas. The values obtained so far probably have already been affected by the mining operations.

5.6 Karst Denudation

Corbel (1957) pioneered the studies of karst denudation on a regional scale. Several measurements have been made throughout the world, although comparatively few were performed in tropical areas, and none in the Brazilian karst. The karst denudation gives an insight on the rate of landscape lowering for a drainage basin. Smith & Atkinson (1976) and Atkinson & Smith (1976) found a positive correlation between denudation rates and runoff. In karst areas the study requires selective sampling of an outlet for calcium and magnesium, data about the discharge of the basin (or runoff derived from precipitation and evaporation), and the drainage basin area. Although much can be said about possible misassumptions underlying the method (see Ford & Williams, 1989), it remains a useful tool for comparing karst evolution in different parts of the world.

Effects of variation in paleoclimates in the tropical karst of Brazil are still not well understood. It is likely that the Matozinhos-Pedro Leopoldo Karst did not experience sharp variations in temperature during Quaternary glaciations, but wetter periods have occurred in the past (Lanari, 1909), attested by an episode of more intense speleothem deposition. Therefore, the general amount of runoff is likely to have changed somewhat during the evolution of the karst landscape. The denudation values obtained are preliminary in scope due to the small number of water samples per basin.

Drainage in the Matozinhos-Pedro Leopoldo Karst is mainly autogenic, although in some portions there are small areas of phyllite overlying the limestone (see section 4.4). In the calculations of denudation the phyllite lenses were not taken in account, due to their small areal extent. Calculations were performed separately for the identified drainage basins. A bulk density of 2.5 g/cm^3 was assumed for the limestone. The values of carbonate ions Ca and Mg in the springs were averaged for the wet and dry periods. Denudation was calculated for both wet and dry periods, using the measured discharge for each period. There is an almost even yearly relation between wet and dry months; thus the results were averaged, giving the final denudation rate for each drainage basin. Jaguara Drainage Basin was not included since most of its catchment surface lies outside the study area. Cauê and Olho d'Água Springs, located in the final stages of the thesis, have very little chemical data. No denudation rate was calculated for these two basins. Table 5.14 gives the denudation rates for the drainage basins.

	Samambaia	Palmeiras-Mocambo	Moinho Velho
Denudation Rates	10	79	140

Table 5.14 Denudation rates for selected drainage basins. Values in millimeters per thousand years.

The very low denudation value at Samambaia Drainage Basin is probably largely affected by water exploitation along its aerial portion. The other drainage basins show more realistic data, since they have not been substantially affected by anthropogenic modification. The denudation during wet periods was higher for Samambaia Basin but lower for Palmeiras-Mocambo Basin. Considering imprecisions in the delimitation of the drainage basins, a denudation rate between 70-150 mm/ka^{-1} is preliminarily assumed for the Matozinhos-Pedro Leopoldo Karst. This rate, although high compared with the fitting curve of Atkinson & Smith (1976), is in accordance with rates obtained in other tropical karst areas such as the Cave Branch area, Belize (90 mm/ka) (Miller, 1981), Sarawak (80 mm/ka) (Day, 1981), Mexico (80-100 mm/ka) (Fish, 1978 quoted by Miller, 1981) or Guilin, China (89.68 mm/ka) (Sweeting, 1990). A more continuous monitoring is recommended in order to refine the results.

5.7 Conclusions

Diffuse-flow probably predominates in Moinho Velho and Jaguara Springs. Moinho Velho Spring does not show any significant increase in discharge during the wet season, although it follows the general trend of hardness dilution. The temperature also remains fairly constant throughout the year. The data suggest that these drainage basins do not have surface exposure sections. Basins with surface sections such as Mocambo and Samambaia show higher temperature variations. In these basins conduit-flow predominates.

The hardness concentrations show a well marked decrease due to dilution during the summer. Even for springs with hypothesized diffuse flow there was a marked variation in calcium, probably related to the contribution of unsaturated recharge water, which does not allow the water to become saturated during the wet season.

The seasonal variation in runoff appears to be the most important control over the water chemistry since it affects the concentration of the major ions -- even in springs with major diffuse flow component, such as Moinho Velho and Jaguara Springs. Soil CO_2 availability at different seasons may also be an important factor.

The low concentration in ions other than calcium and magnesium are due to the autogenic nature of the karst water, not having significant drainage over rocks other than limestone. It shows that the groundwater pollution by chemical elements is negligible, despite the important human occupation in the area.

The denudation rate of 70-150 $mm.ka^{-1}$ agrees with other estimates from tropical karst areas. A correlation between drainage basin area and karst denudation rates was not observed. The wet period tends to show either increase or decrease in the denudation rates, depending on the drainage basin. The anomalously low results obtained at Samambaia Basin may be affected by drainage basin degradation.

CHAPTER 6 PALEOHYDROLOGY

Most of the caves in the studied area are dry, isolated from present day hydrological processes. They are situated above the valleys or in the middle of sinkhole slopes. These caves are remnants from a past hydrological network that existed over the area. The analysis of flow marks on cave walls and ceilings can indicate the flow direction that formed the cave. Scallops are small-scale, ripple-like features commonly found in caves (Goodchild & Ford, 1971). Curl (1974) gives equations and general rules to find past flow velocity and flow direction through analysis of scallops. The scallop length is inversely related to the flow velocity. Observations made in 54 dry caves allowed the determination of the general flow direction in these caves and its comparison with the present day hydrogeology outlined in chapter 4.

6.1 Methods

Over 300 caves have been identified in the Matozinhos-Pedro Leopoldo Karst. The 54 studied caves do not have a perennial stream or lake. The only hydrological activity inside these caves is dripping cause by percolation water or invasion runoff during severe storms. Some caves have undergone massive modification by both chemical deposition and clastic sedimentation. Relict levels of calcified, fine-grained sediments are found inside most of the caves. A cyclic sequence of sedimentation and outwash appears to have occurred. Also, the formation of speleothems can mask the original shape of the conduit. These two types of modifications change the profile of the cave, making it difficult to recognize the flow direction.

No radiometric dating has been made in the Matozinhos-Pedro Leopoldo Karst. Kohler (1989) believes that the genesis of these caves may have occurred during late Pleistocene. In the studied sample, the caves may have become dry at different periods. Therefore, not being uniform in age, the flow patterns deduced from the caves may not have occurred simultaneously. The purpose of the study was to correlate past groundwater flow, regardless of its age, with the present flow directions.

Curl (1974) describes the formation of scallops (Figure 6.1). The steeper slope of the scallop indicates the upstream side. A mechanical device to record scallop profiles has been designed by Lauritzen (1981). In this study, visual inspections of several sections of cave walls were performed in all caves. The scallops are generally medium sized (around 10 centimeters) although very large ones are commonly found at sites formerly occupied by paleolakes. Small scallops due to rapid flow were also observed.

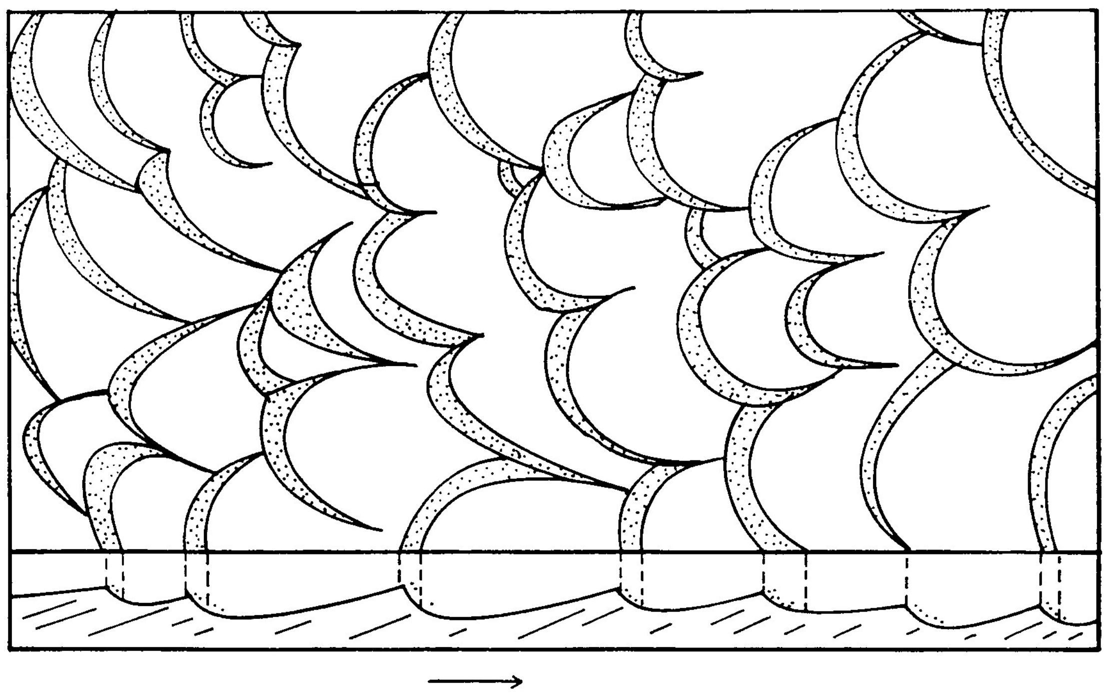


Figure 6.1 Plan View and Lateral Section of Scallops (Bögli, 1980)

In most of the caves the walls are smooth, and the scallops are not well defined. It appears that dissolution by water vapor in the cave air or under sediment covering may have played a role in masking the scallops. In one cave (Caieiras Cave), primitive human incisions in the cave wall apparently were weathered, becoming less noticeable closer to the entrance. Water vapor dissolution is a possible explanation for this phenomenon. The hot and humid climate may favor this process. Cave passages with their floor covered by sediment are a very common occurrence. Uniform dissolution under the sediment may have smoothed the cave walls. Later sediment removal would have exhumed entire sections of caves. Caves with active drainage have well defined scallops.

The results obtained were divided into three categories. In some caves the scallops are not visible at all. In other caves the flow points to a random direction, suggesting backflooding or changing directions. These two types of caves have a 'undetected paleoflow.' Other caves show nonprominent scallops, where flow direction was determined with uncertainty. These caves have a 'poorly defined paleoflow' direction. Other caves have a 'well defined paleoflow' direction through well preserved scallops. In some situations, other cave features such as ceiling meanders, wall pockets and sediments were used to confirm suspected flow directions. Table 6.1 shows the flow characteristics in the caves studied. Appendix A shows the location of these caves.

Cave	Reference number	Flow
Galinheiro	1	PD
Entrada Alta	2	PD
Borges	3	PD
Encanação	4	PD
Baú	5	WD
Vargem	6	WD
Lapinha I	7	WD
Lapinha II	8	WD
Lapinha III	9	WD
Corredor de Pedra	10	PD
Labirinto Fechado	11	PD
Buraco do Frederico	12	WD
Faustina	13	WD
Boca	14	WD
Itapucú	15	PD
Milagres	16	WD
Periperi I	17	WD
Periperi II	18	WD
Ballet	19	WD
Chapéu	20	PD
Poções	21	WD
Paredão dos Poções I	22	WD
Paredão dos Poções II	23	WD
Escadas	24	WD
Trincheira	25	WD
Lavoura	26	WD
Caieiras	27	PD
Cacimbas	28	WD
Esquecida	29	WD
Vargem da Pedra	30	PD
Forno de Cal	31	WD
Couvelabro	32	PD
Perdidas	-	U
Tombo	-	U
Estudantes	-	U
Túneis	-	U
Feitiço	-	U
Lapinha	-	U
Paredão da Lapinha (10 small caves)	-	U
Facão Perdido	-	U
Mortuária	-	U
Dois condutos	-	U
Jibóia	-	U
Retiro	-	U

Table 6.1 List of dry caves studied. WD - Well Defined paleoflow, PD Poorly Defined paleoflow, U - Undetected paleoflow. The latter is not shown in the figures.

Flow direction represented as a single vector was plotted on a map. Caves, especially in low gradient karst areas, are known to meander. The vector might not represent the precise direction of paleoflow since it might have been obtained in a nonrepresentative section of the cave. Therefore, a margin of tolerance should be included with the acceptance of these values. In addition it must be noted that the active groundwater routes have been represented as a straight line due to the difficulties of defining the precise course of an underground stream. It must be assumed that both the paleoflow directions and the present day flow routes are approximations of the actual flow. For the purpose of general flow direction comparison, a reasonably good overall picture can be obtained even with the limitations discussed above.

6.2 Results

The results obtained are described according to the likely drainage basin. Poorly defined flow direction and well defined flow direction are not distinguished in the figures.

6.2.1 Samambaia Basin

Figure 6.2 shows the paleoflow in this basin. In the upstream section, the paleoflow of the few caves studied, Entrada Alta, Borges and Encanação Caves (No. 2,3 and 4) match well the existing underground hydrology. On the other hand, the downstream section has some intriguing anomalies, with the paleoflow not pointing toward the present local base level, the Samambaia Creek. Some caves point toward the present regional base level (Velhas River) while others are directed toward the Mocambeiro Depression to the west.

6.2.2 Palmeiras-Mocambo Basin

Figure 6.3 shows the direction of flow in the dry caves analyzed. The great majority of the paleoflow in this basin is concordant with the present day active hydrogeology. In the upstream section, the flow in all dry caves analyzed agree with the existing flow directions. The sole exception occurs in the downstream section for Caieiras Cave (No. 27)

Some caves located in the eastern side of this drainage basin may have their paleoflow pointing toward the Mocambeiro Depression (Figure 6.4).

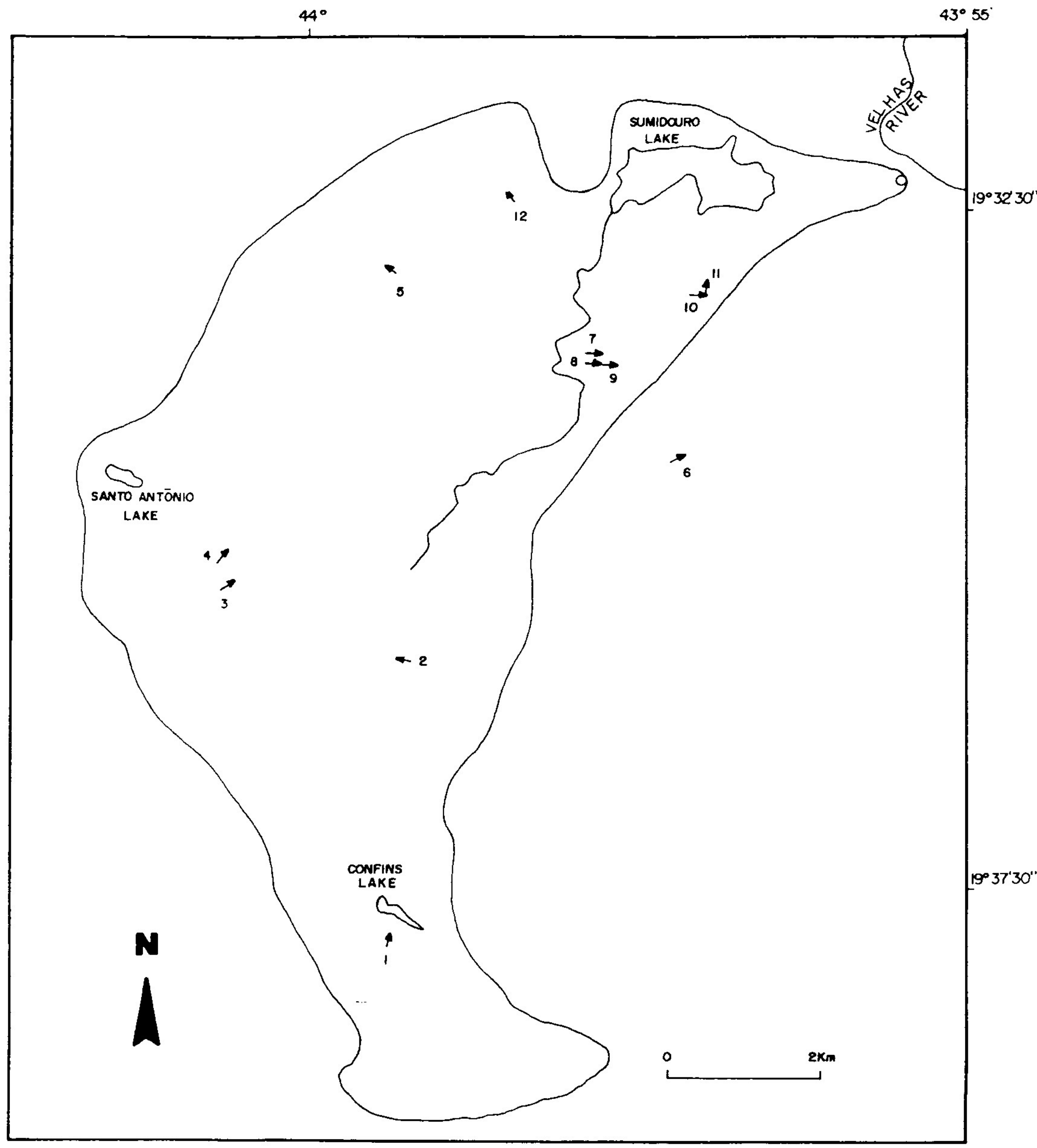


Figure 6.2 Paleoflow at Samambaia Basin. Refer to Table 6.1 for Cave Names

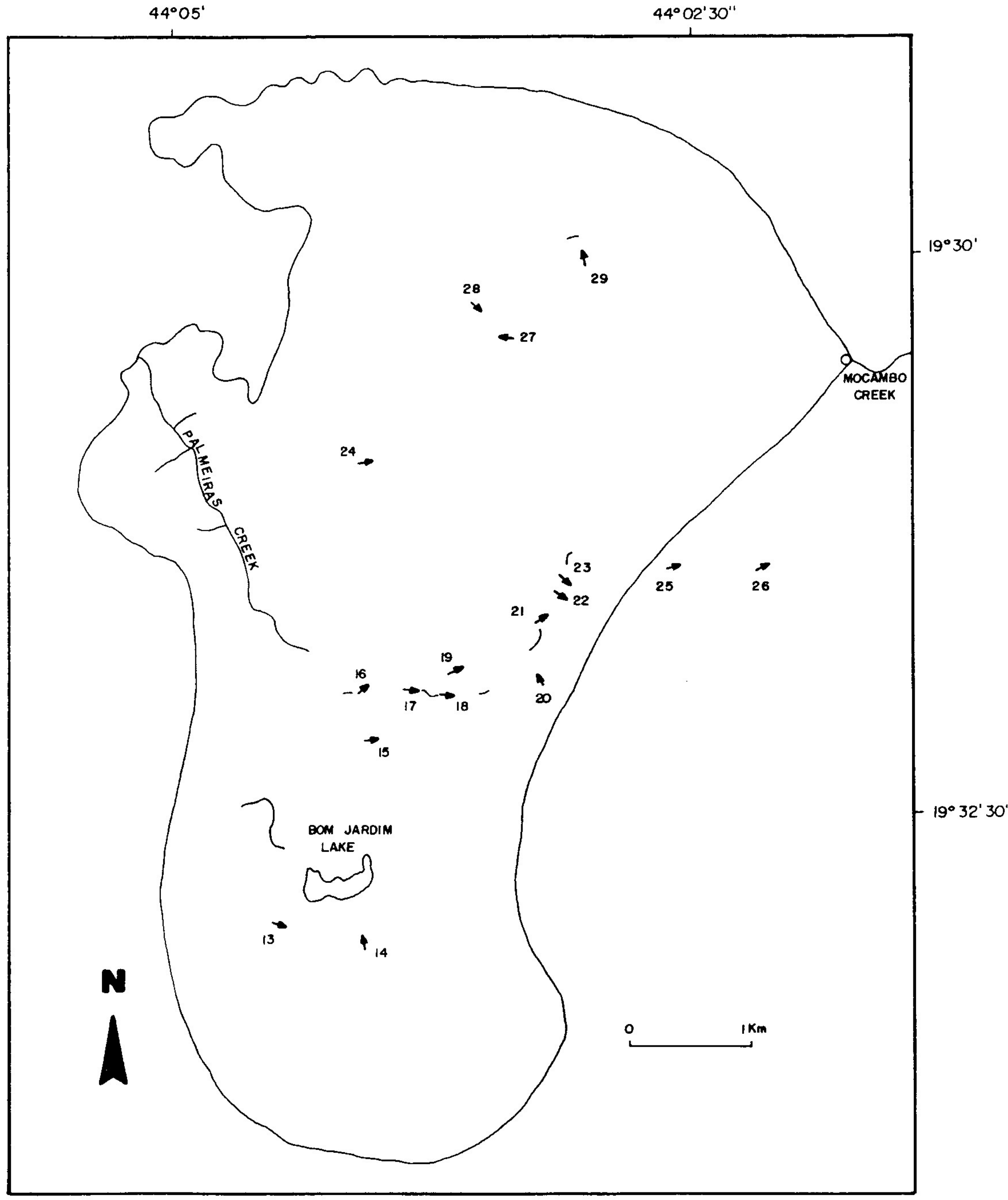


Figure 6.3 Paleoflow at Palmeiras-Mocambo Basin. Refer to Table 6.1 for Cave Names

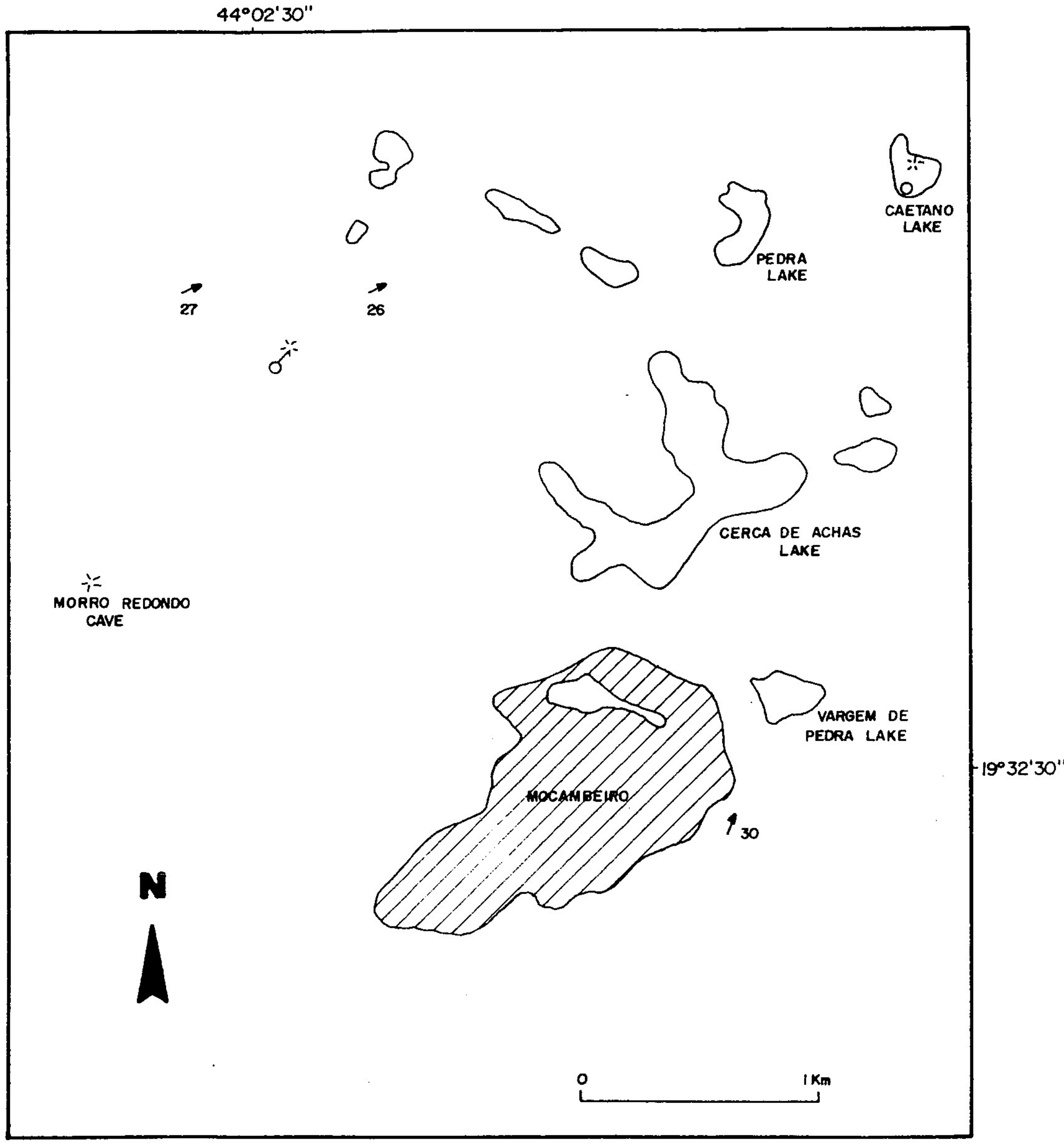


Figure 6.4 Hydrogeological Features and Paleoflow at Mocambeiro Depression. Refer to Table 6.1 for Cave Names

6.2.3 Other Sites

The Moinho Velho Drainage Basin shows one cave, Forno de Cal Cave (No. 31), with paleoflow direction pointing toward the active drainage at Moinho Cave, away from the Moinho Velho Spring (Figure 6.5).

Couvelabro Cave (no. 32) is a relict cave about 20 meters above Mata Creek. Scallops show that it once discharged into the creek (Figure 6.6).

6.3 Discussion

The downstream portion of the Samambaia Basin shows little concordance between the present day hydrology and the paleoflow. Baú and Buraco do Frederico Caves (No. 5 and 12) point toward the Mocambeiro Depression, showing that the limits of the water divide between the Samambaia Basin and the Mocambeiro (Caetano?) Basin were perhaps shifted to the east in the past. Vargem, Lapinha I, II, III and Corredor de Pedra Caves (No. 6 to 10) near the Samambaia Creek have paleoflow toward the present location of Velhas River. It is interesting to note that even in some cliffs by the side of the creek, the ancient flow in the dry conduits is pointing to another direction, toward the present Velhas River channel. It seems likely that the Samambaia Creek did not represent a

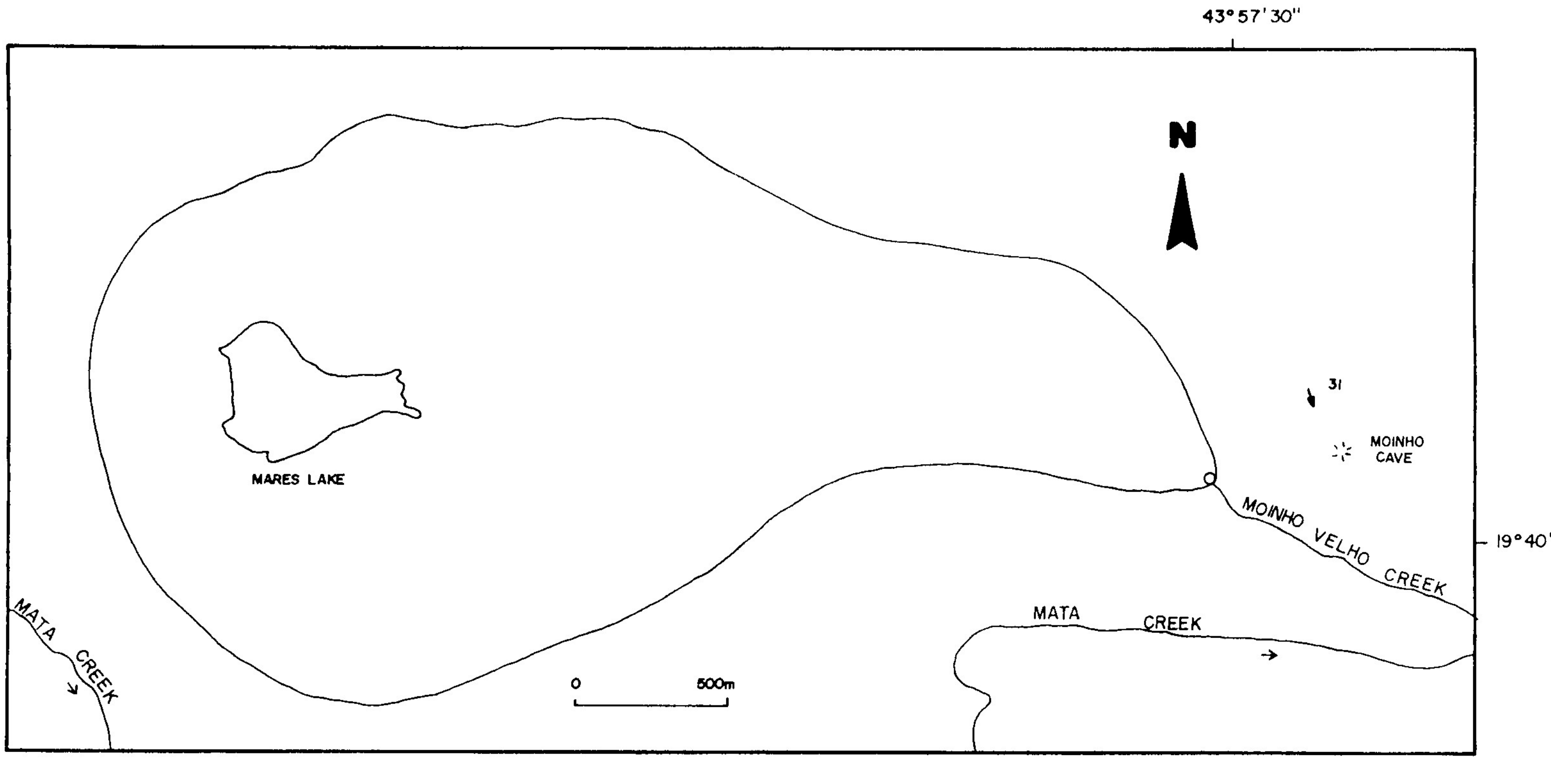


Figure 6.5 Paleoflow at Moinho Velho Basin. Refer to Table 6.1 for Cave Names

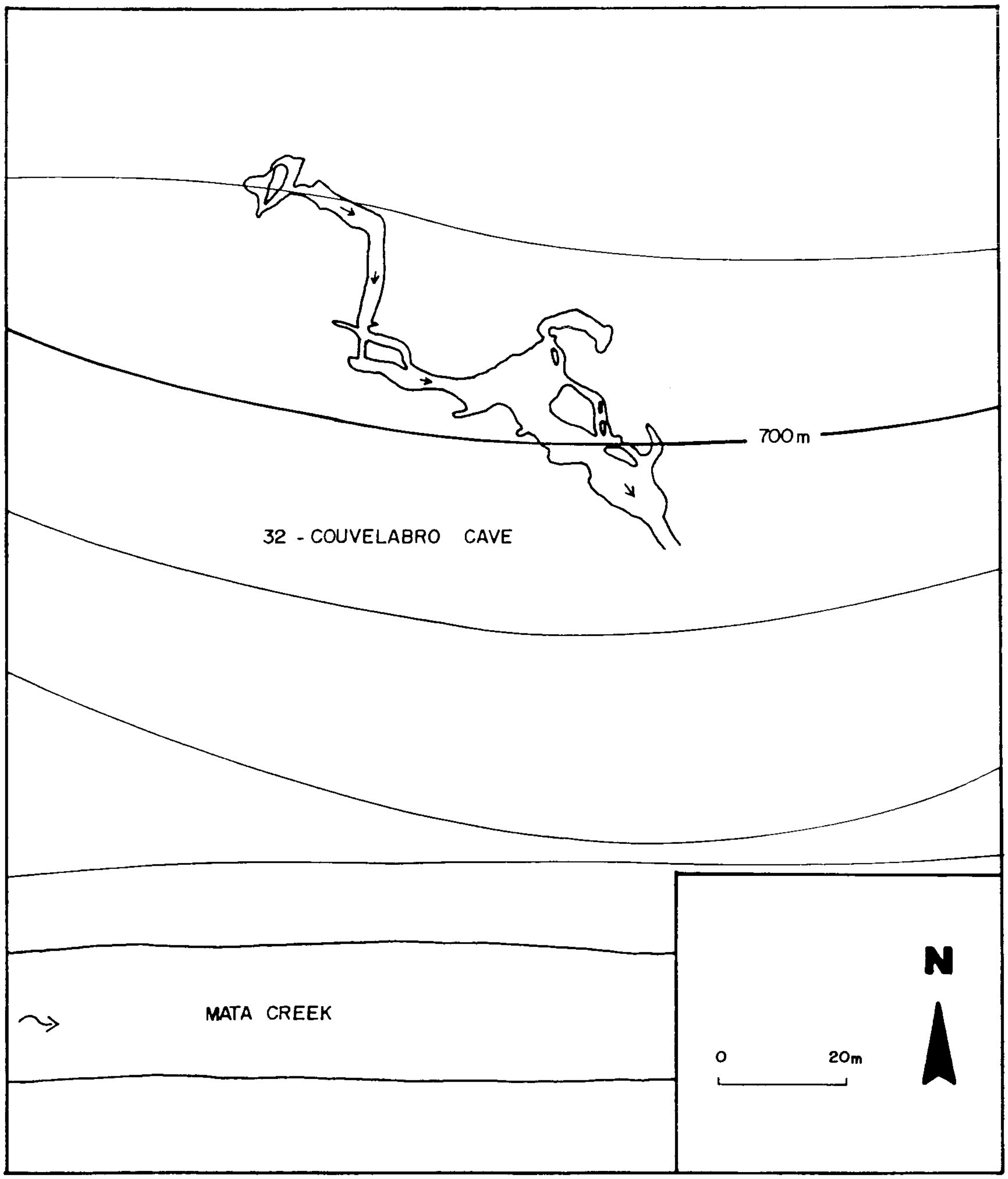


Figure 6.6 Paleoflow at the Margin of Mata Creek. Ten Meter Interval Surface Contour. Cave Survey by N.A.E.

significant base level at the time of genesis of these caves. The groundwater paleoflow ignores the present position of the creek, flowing toward other basins (Mocambeiro) or straight to the present location of Velhas River.

Galinheiro Cave (No. 1), at the probable headwaters of Samambaia Creek, used to discharge into the closed basin now occupied by the Confins Lake. The hydrological behavior of this lake is still unknown. It is believed that it feeds water to the Lapa Vermelha I Cave, although no swallet is visible. The lake level shows little variation throughout the year, regardless of the rainfall. Galinheiro Cave used to input water into the lake. Some hydrological connection to Samambaia Basin is therefore likely to have existed in the past, and may exist today.

The dry caves at the Palmeiras-Mocambo Basin show a concordant paleoflow direction when compared to the active routes. The general drainage flow pattern does not appear to have changed much in that area. There is convergent paleoflow in the upstream portion and more uniform flow directions with some tributaries such as Chapéu Cave (No.20) in the downstream portion. There is no evidence of a major allogenic paleostream entering this basin as suggested by Kohler (1989). Evidence points toward multiple autogenic input points that used to join forming the ancient drainage.

Both past and present flow within the Moinho Velho Basin are not related to the active major spring in the area. This spring is probably more recent, not representing the outlet of the more mature karst conduits.

6.4 Conclusions

The data suggest that the Palmeiras-Mocambo Basin is a more mature drainage basin than the Samambaia Basin since its flow pattern at the time of genesis of today's dry caves resembles the present flow pattern. Some portions of Samambaia Basin had probably a more recent development. Ancient flow in the dry caves in the downstream portion of this basin points toward other active base levels such as the Mocambeiro Depression and Velhas River.

The general paleounderground flow trend at the Matozinhos-Pedro Leopoldo Karst matches well the present groundwater flow routes. Past groundwater flow used to discharge at the approximate location of today's Velhas River. Mata Creek was also an important base level.

CHAPTER 7 OVERALL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The Matozinhos-Pedro Leopoldo Karst is a well-developed karst area possessing a well-developed groundwater flow system and a full range of all typical karst landforms.

The karst recharge water is basically autogenic, with a small contribution from phyllite areas. About 88% of the identified groundwater flow discharges at Velhas River, the major base level for the area. The remaining 12% flows toward Mata Creek.

Samambaia and Palmeiras-Mocambo are the two best developed drainage basins in the area, having both underground and surface sections. Samambaia Creek works as a local base level, concentrating the flow toward a series of springs along its margin. Palmeiras Creek has fewer tributaries, flowing essentially toward Velhas River. The flow in the upper portion of the study area tends to be faster and turbulent. In the lower reaches the gentler hydraulic gradient causes slower phreatic flow to take place.

Optical brightener and fluorescein had a poor performance as water tracers in this area, probably due to the characteristics of the Brazilian optical brightener, as well as due to adsorption or photochemical decay for both dyes. The low performance of the dyes was also caused by the existence of lakes in swallets and springs, causing dye dilution.

Some springs show evidence of predominant diffuse flow, such as constant temperature and little variation in discharge throughout the year. This is the case of Moinho Velho and Jaguara Springs. However, all springs show a sharp decrease in hardness during the wet season due to dilution, suggesting that replenishment by recharge water and/or fast flow during the rainy season may take place not allowing sufficient time for the water to achieve saturation. Conduit flow predominates in the major basins, such as Samambaia and Palmeiras-Mocambo. The annual trend of major ions dilution in all springs is determined by the seasonal variation in runoff. It affects both diffuse-flow and conduit-flow springs. Soil CO_2 availability due to the rainfall pattern may also play a role. Chemical water quality is good for the area.

Samambaia Basin has been heavily exploited by dams and water pumping. The overall water budget may have been severely affected.

A preliminary denudation rate of 70-150 mm/ka^{-1} obtained by four drainage basins is concordant with values from other tropical karst areas.

Paleoflow studies indicate that the downstream section of Samambaia Basin used to discharge to the east, toward Velhas River or to the west toward Mocambeiro Depression. The present hydrological features located downstream, such as Sumidouro Lake, are possibly more recent. Palmeiras-Mocambo Basin paleoflow has changed little since the time of speleogenesis of the dry caves.

The general pattern of groundwater circulation in the Matozinhos-Pedro Leopoldo Karst in the past shows that flow evolution and cavern genesis have been controlled by Velhas River and Mata Creek, similarly to that occurring today.

7.2 Recommendations for Further Research

This thesis represents a first characterization of the karst hydrology of the Matozinhos-Pedro Leopoldo region. It was a generic study of a very large area. Other research focusing on more specific topics and encompassing smaller areas would increase the understanding of the active and past processes envolved in the genesis of this karst area.

Some important underground drainage connections were not traced successfully. The hypothetical hydrological connections between Lapa Vermelha swallet and Samambaia Spring as well as between Sumidouro Lake and Poço Azul Spring, among others, need to be confirmed. A tracing experiment during exceptionally dry years would avoid the major problem of dye dilution in the lakes. Minor swallets or even dry sinkholes could be traced during the wet season or storm events. This additional data would help increase the accuracy of the delineated drainage basins and provide data on other nondetected underground drainage basins.

The cause of the poor performance of optical brightener and fluorescein in the area (and also in other tropical areas throughout the world) have not been determined. An investigation on the flow behavior of these dyes in tropical karst areas would be of interest of hydrogeologists. Also, other tracing techniques best suited for tropical conditions should be attempted.

A more detailed monitoring of the karst springs should be performed. Data-loggers running through an entire hydrological cycle and detailing the flow and hydrochemical variation during storm events would provide a much improved view of the subsurface hydrological processes. Groundwater quality periodical sampling should be continued. Bacterial data and additional biological parameters should be included in the analysis.

Dating of the cave sediments by some of the several methods available (uranium series disequilibrium, ESR, paleomagnetism, among others) would represent a quantum leap in determining the timescales of karst development and would help in building a chronological sequence for the evolution of the Matozinhos-Pedro Leopoldo Karst.

Appendix A

LOCATION OF FEATURES DESCRIBED IN THE TEXT

CAVES	LATITUDE	LONGITUDE
Água de Matozinhos	19°33'22" S	44°04'30" W
Água Fria	19°34'49" S	44°00'06" W
Água Surda	19°29'51" S	44°03'20" W
Ballet	19°31'56" S	44°03'35" W
Baú	19°33'12" S	43°59'24" W
Boca	19°33'07" S	44°04'04" W
Bomba	19°33'20" S	44°03'37" W
Bom Jardim	19°32'57" S	44°04'09" W
Borges	19°35'20" S	44°00'32" W
Buraco do Frederico	19°32'26" S	43°58'26" W
Cacimbas	19°30'14" S	44°03'36" W
Caieiras	19°30'29" S	44°03'23" W
Chapéu	19°31'50" S	44°03'14" W
Corredor de Pedra	19°33'08" S	43°56'59" W
Couvelabro	19°41'53" S	43°53'44" W
Curral	19°32'34" S	43°59'25" W
Dois Condutos	19°31'48" S	43°58'44" W
Encanação	19°35'05" S	44°00'34" W
Entrada Alta	19°35'51" S	43°59'07" W
Escadas	19°30'59" S	44°04'05" W
Esquecida	19°30'04" S	44°03'05" W
Estudantes	19°31'28" S	44°03'26" W
Facão Perdido	19°31'47" S	44°02'57" W
Faustina	19°33'02" S	44°04'42" W
Feitiço	19°33'36" S	43°57'35" W
Forno de Cal	19°39'44" S	43°57'21" W
Foto Aérea	19°29'30" S	44°03'46" W
Francês	19°32'45" S	43°58'46" W
Freática	19°30'05" S	44°03'24" W
Galinheiro	19°38'00" S	43°58'06" W
Itapucú	19°32'01" S	44°04'01" W
Jibóia	19°31'26" S	44°02'58" W
Labirinto Fechado	19°33'09" S	43°56'59" W
Lapa Vermelha I	19°36'42" S	43°59'44" W
Lapinha	19°33'40" S	43°57'30" W
Lavoura	19°31'27" S	44°02'14" W
Milagres	19°32'01" S	44°04'01" W

Moinho	19°39'49" S	43°57'19" W
Morro Redondo	19°32'07" S	44°02'53" W
Mortuária	19°38'21" S	43°58'46" W
Paredão da Lapinha I	19°33'38" S	43°57'48" W
Paredão da Lapinha II	19°33'38" S	43°57'48" W
Paredão da Lapinha III	19°33'39" S	43°57'48" W
Paredão da Lapinha (10 other small caves)	19°33'38" S	43°57'48" W
Paredão de Poções I	19°31'36" S	44°03'12" W
Paredão de Poções II	19°31'31" S	44°03'05" W
Paredãozão	19°36'10" S	43°59'09" W
Perdidas	19°31'29" S	44°03'07" W
Periperi I	19°31'59" S	44°03'49" W
Periperi II	19°32'01" S	44°03'42" W
Perobas	19°32'31" S	44°04'21" W
Poções	19°31'43" S	44°03'14" W
Retiro	19°39'49" S	43°57'07" W
Tombo	19°30'07" S	44°01'42" W
Trincheira	19°31'27" S	44°02'59" W
Túneis	19°33'40" S	43°57'37" W
Varzea	19°34'05" S	43°56'52" W
Vargem da Pedra	19°32'40" S	44°01'21" W

SPRINGS

Cauê	19°37'14" S	44°01'04" W
Debris	19°32'48" S	44°04'20" W
Engenho	19°34'50" S	43°59'07" W
Gameleira	19°33'02" S	43°57'48" W
Horta Palestina	19°32'59" S	43°58'01" W
Jaboticatuba's Olho d'Água	19°31'32" S	43°55'23" W
Jaguara	19°29'35" S	44°00'53" W
Lagoa da Mata	19°32'19" S	43°55'15" W
Mocambo	19°30'28" S	44°01'50" W
Moinho Velho	19°39'53" S	43°57'24" W
Olho d'Água	19°41'30" S	43°53'15" W
Palestina	19°32'58" S	43°57'58" W
Poço Azul	19°32'15" S	43°55'25" W
Samambaia	19°35'11" S	43°59'08" W
Sítio Santo Antônio	19°35'43" S	44°03'06" W

OTHER FEATURES

Baldo Swallet	19°33'04" S	43°56'07" W
Ballet Sinkhole	19°31'59" S	44°03'30" W
Bom Jardim Swallet	19°32'44" S	44°04'03" W
Caetano Spring and Swallet	19°31'09" S	44°00'56" W
Captação Swallet	19°32'44" S	44°04'25" W
Chácara Sinkhole	19°32'46" S	43°59'47" W
Cocho d'Água Karst Window	19°34'38" S	44°00'00" W
Goiaba Swallet	19°33'08" S	43°56'52" W
Milagres Sinkhole	19°32'01" S	44°04'01" W
Palmeiras Swallet	19°31'49" S	44°04'20" W
Poções Lagoons Swallet	19°31'19" S	44°03'07" W
Poções Cave Swallet	19°31'43" S	44°03'14" W
Sacota Sinkhole	19°32'01" S	44°03'42" W
Sumidouro Lake Swallet	19°32'29" S	43°56'31" W
Zé Irene Sinkhole	19°29'57" S	44°03'07" W

Appendix B

LIST OF DYE TRACES PERFORMED

I- Input point
R- Receptor
N- Negative result
P- Positive result

October 11, 1991	Background dye

Mocambo Creek (N)
Samambaia Creek (N)

November 10, 1991	1.5 kg of fluorescein

IP - Morro Redondo Cave

R1 - Mocambo Spring (N)
R2 - Jaguara Spring (N)

December 5, 1991	3.5 kg of optical brightener

IP - Sumidouro Lake

R1 - Poço Azul Spring (N)
R2 - Lagoa da Mata Spring (N)
R3 - Jaboticatuba's Olho d'Água (detector not found)

December 5, 1991	1 kg of fluorescein

IP - Baldo Swallet

R1 - Poço Azul Spring (N)
R2 - Lagoa da Mata Spring (N)
R3 - Jaboticatuba's Olho d'Água (detector not found)

December 5, 1991 1.7 kg of optical brightener

IP - Poções Swallet

R1 - Jaguara Spring (N)
R2 - Mocambo Spring (N)

February 16, 1992 250 g of fluorescein

IP - Moinho Cave

R1 - Moinho Velho Spring (N)

April 1, 1992 800 g of fluorescein

IP - Palmeiras Swallet

R1 - Milagres Spring (P)
R2 - Sacota Spring (P)
R3 - Ballet Spring (N)

June 30, 1992 2.5 kg of fluorescein

IP - Bom Jardim Lake Swallet

R1 - Sacota Spring (N)
R2 - Ballet Spring (P)
R3 - Poções Lagoons (P)
R4 - Mocambo Spring (P)

June 30, 1992 2 kg of optical brightener

IP - Sacota Swallet

R1 - Ballet Spring (detector not found)
R2 - Poções Lagoons (N)
R3 - Mocambo Spring (N)

July 27, 1992 2.5 kg of fluorescein

IP - Sacota Swallet

R1 - Mocambo Spring (P)
R2 - Poções Lagoons (P)
R3 - Ballet Spring (P)
R4 - Poções Spring (P)

July 30, 1992 300 g of fluorescein

IP - Captação Swallet

Visual observation at Bom Jardim Lake

November 24, 1992 500 g of fluorescein

IP - Francês Hole

R1 - Palestina Spring (P)

November 25, 1992 500 g of fluorescein

IP - Curral Cave

R1 - Francês Hole (P)

February 15, 1993 700 g of fluorescein

IP - Água Fria Cave

R1 - Cocho d'Água Karst Window (P)
R2 - Engenho Spring (P)

February 15, 1993 3.5 kg of optical brightener

IP - Cocho d'Água Karst Window

R1 - Engenho Spring (N)

May 5, 1993 210 g of fluorescein

IP - Moinho Cave

R1 - Moinho Creek upstream (N)
R2 - Moinho Creek upper middle (N)
R3 - Moinho Creek lower middle (N)
R4 - Moinho Creek downstream (N)

May 12, 1993 2 kg of fluorescein

IP - Zé Irene Karst Window

R1 - Jaguara Spring (N)
R2 - Mocambo Spring (P)

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