GROUNDWATER POLLUTION RISK AND VULNERABILITY MAP OF THE SAO PAULO STATE - BRASIL

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ABSTRACT

Aiming to provide a global diagnosis of the actual threat of pollution to the most important aquifers of the State of São Paulo, Brasil, due to its intensive industrialization and agriculture practices, three government institutions - the Instituto Geológico (Geological Institute), the CETESB (Environmental Sanitary Technology Company) and the DAEE (Water and Eletrical Energy Department) - carried out a regional survey for defining the aquifers vulnerability to pollution and for recording and ranking the potential contaminant sources.

This paper describes the results of this survey, excluding the metropolitan area of the city of São Paulo. More than 500 industries were recorded and ranked according to their low, moderate or high potential contaminant load for impacting groundwater. Thirty one aquifer units were defined and a 1:500.000 scale vulnerability map was produced.

Critical areas were defined and recommended as being priority sites for the adoption of control measures.

KEYWORDS:

Groundwater pollution; protection; risk analysis; vulnerability mapping potencial contaminant load

INTRODUCTION

Nowadays, over 20,000 deep wells and an inmeasurable number of shallow, hand-dug wells furnish water for public supply, industrial use and crops irrigation in the State of São Paulo.

The intensive degrees of industrialization and agriculture practices, together with the indiscriminate groundwater abstraction regime have, however, threatened the usually excellent natural quality of these important water reserviours, thus demanding the urgent adoption of planning and control measures before they become irreparably damaged.

In order to provide a global diagnosis of the pollution threat of the most important aquifers of the State of São Paulo, three government institutions, the Instituto Geológico (Geological Institute), the CETESB (Environmental Sanitary Technology Company) and the DAEE (Water and Eletrical Energy

The two components of the aquifer vulnerability involve knowledge of many aquifers intrinsic characteristics, like permeabilities (hidraulic conductivities), porosities, cation exchange capacity, unsaturated zone mineral composition, and thickness of unsaturated zone, etc., informations usually not available.

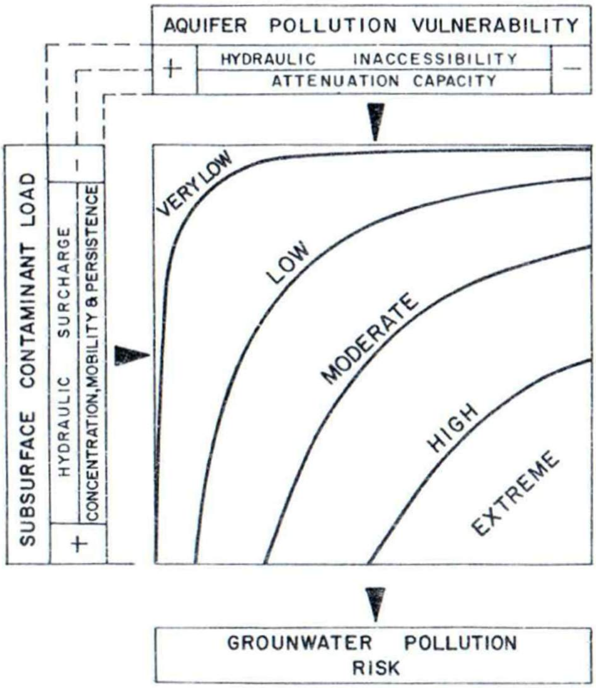


Fig. 1. Conceptual scheme of groundwater pollution risk (modified from Foster, 1987)

For this reason an empirical methodology (Foster, 1987) proposed for the evaluation of aquifer pollution vulnerability was used (Fig. 2). It involves only three discrete and fudamental stages usually available which summarizes all of the intrinsec aquifers properties.

The first component, and most fundamental, is groundwater occurence, in terms of the aquifer Degree of confinement. The higher the confinement degree, the smaller the aquifer vulnerability. The critic cases are thus, unconfined water-table aquifers.

The second factor is the Overall lithology of the overlying strata. This scheme was built considering the intrinsec hydrological and geochemical properties of the litologies, their degree of fissuring and consolidation.

The third factor is the Depth to the groundwater table or strike (for confined aquifers). The higher the depth, the smaller the vulnerability index, once the travel time in the unsaturated zone encreases, and so does the attenuation capacity.

As it can be seen in Fig. 2 to each vulnerability component class is given a number, from 0 to 1.0 for component number one (groundwater occurence), and from 0.4 to 1.0 for the two other factors. The multiplication of the three

Department) carried out a regional study with the main purpose of defining the aquifers' natural vulnerability to pollution, recording and ranking the potential contaminant sources, and critical areas of groundwater pollution risk.

THE CONCEPT OF GROUNDWATER POLLUTION RISK

The methodology used is an adaptation of the originally proposed report by the Pan-American Health Organization (PAHO) (Foster and Hirata, 1988) by which the concept of groundwater pollution risk (Fig. 1) can be stated as the interaction of two main components:
(a) "the pollution load that is, will be on might be applied on the subsurface environment as a result of human activity", and
(b) "the aquifer pollution vulnerability, consequent upon the natural characteristics of the strata separating it from the land surface".

This concept of pollution risk is defined as the probability that groundwater in an aquifer will become contaminated to concentration above the WHO guideline values for drinking water quality, but does not refers to the water supplies already stablished, once such analysis is highly dependent upon specific site hydrogeological conditions.

By such a scheme in Fig. 1, we can have situations of high natural aquifer vulnerability but virtually no risk of groundwater pollution, when the contaminant load is low or absent and viceversa. The extreme risk would occur when both the contaminant load is expressive and the aquifer highly vulnerable.

Such type of work intends to be a method of rapid assessment using existing date and hydrogeological surveys available, without necessarily utilizing aditional resources or activities, to prioritize groundwater protection efforts.

It does not however, substitute the necessary field surveys and follow-up control measures and groundwater quality monitoring.

METHODS AND PROCEDURES FOR REGIONAL EVALUATION

Characterization of Aquifers Natural Vulnerability

The term aquifer pollution vulnerability represents the sensitivity of an aquifer to being adversely affected by an imposed contaminant load (Foster, 1987; Foster and Hirata, 1988). It is a function of:
(a) the hidraulic inaccessibility of the unsaturated zone; and
(b) the attenuation capacity of the strata overlaying the saturated zone (unsaturated zone or aquitards, for confined aquifers).

The higher the hydraulic inaccessibility, the smaller the aquifer vulnerabilty, once the infiltration water is the most important pollutants transport medium to the groudwater. In the same way, the higher the attenuation capacity of the overlying strata the higher the rates of biodegradation chemical immobilization, physical filtration etc. the pollutants will suffer, the lesser their chances in reaching the water table in significative concentrations are. The unsaturated zone is, in this respect, very important because most of these reactions occurs mainly under unsaturated conditions.

These two factors are subject to interact with the following elements of the contaminant load.
(a) the mode of contaminant disposition in the subsurface and, in particular, the magnitude of any associated hydraulic loading, and
(b) the contaminant class, in terms of its mobility and persistence.

indexes would give the Aquifer Pollution Vulnerability Index, which represented in a map format.

A number of approximations and generalizations are necessary to aplly this method, once the required data for the risk assessment is commonly not available. Therefore one should be aware of the three following cautionary words (Andersen, 1987) when appling the method proposed:
(a) "a general vulnerability to a universal contaminant in a typical pollution scenario is a meaninless concept",
(b) "all aquifers are vulnerable to persistant, mobile contaminants in the long term", and
(c) "less vulnerable aquifers are not easily contaminated, but once polluted they are more difficult to restore".

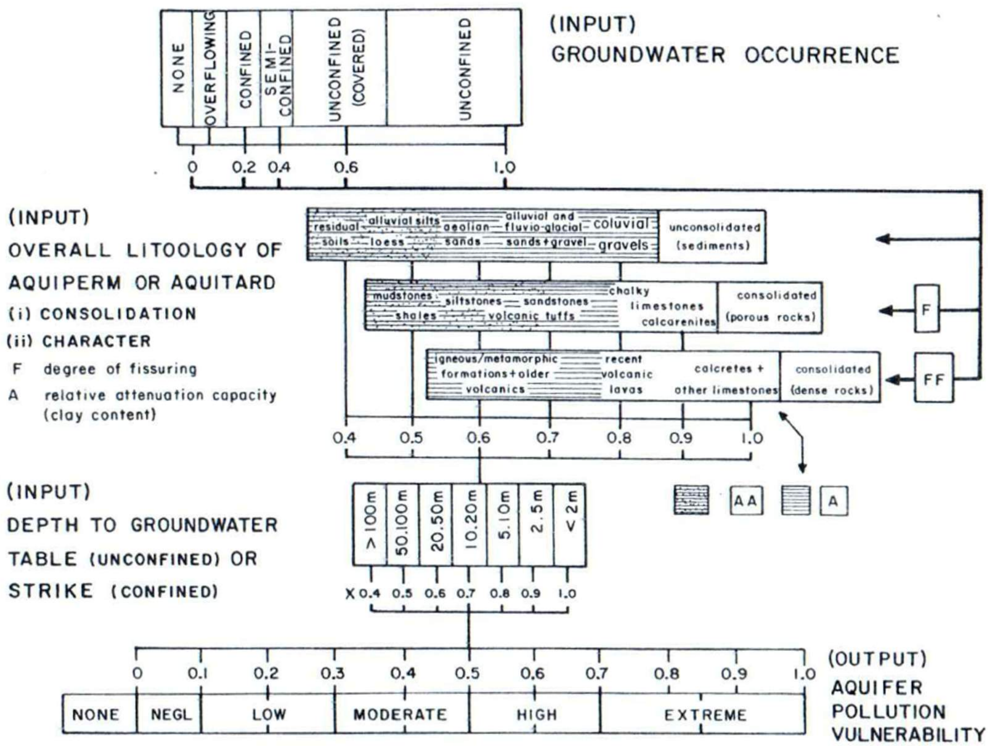


Fig. 2. Scheme of evaluation of aquifer vulnerability index (after Foster, 1987)

Characterization of Potencial Contaminant Load

The subsurface contaminant load generation was evaluated according to the various pollution sources categories, having in mind the following factors:
(a) the class of contaminants involved, i.e. their tendency in being "in-situ" attenuated, their mobility and persistency;
(b) the intensity of the eventual pollution, i.e. the relation between the proportion of recharge area potentially affected (point, diffuse sources) and the expected pollutant concentrations,
(c) the mode of disposition of the pollutants, i.e. adequate or inadequate, hydraulic loading rate, presence of groundwater protection features etc.; and
(d) the duration of the application of the contaminat load.

Due to the practical constraints in obtaining all these informations necessary to perform a contaminant load assessment, the pollution generating activities were ranked in terms of their potential hazard.

The potential contaminant hazard of the urban and economical activities was classified according to the criterion summarized on table 1 the process of classification is discussed in details in Hirata and Bastos (1990) and Bastos et al. 1990 and is outside the scope of this work. Also refer to Foster & Hirata (1988) for exaustive discussions and guidelines for more detailed assessment.

Characterization of Groundwater Pollution Risk Areas

The interaction of aquifers natural vulnerability, represented in map, with potencial contaminant load, determines areas with different leve of groundwater pollution risk.

The groundwater pollution risk and vulnerability map, in a regional level, will constitute the technical basis for the planning of governamental control actions and other aquifers protection measures. The results of this survey should be considered as only a first step in groundwater pollution risk evaluation. They can and should be used to assign priorites for follow-up field investigations and monitoring programs, appropriate to the nature of the subsurface contaminant load and the hydrogeological conditions.

Carthography of the Aquifers Natural Vulnerability

The proposed methodology allowed the definition of the aquifers natural vulnerability in the scale 1:500.000, and the recognition of the more areas or less sensitive to pollution.

Using the basic geological map of the State (IPT, 1981), 31 aquifer units were defined, many of them being coincident to the geological formation. More complex stratigraphycal units, like Irati and Corumbataí formations, were identified as the Passa Dois Aquifer. In the same way, Pirambóia and Botucatu formations, were reconized as Botucatu Aquifer. The sparcely occuring cenozoic formations (Rio Claro, Itaqueri and others) were not distinguished due to the simplification of this work for the International Seminar.

The Fig. 3 shows, for each sedimentary unit of the Paraná Basin, a resume of the principal aquifer occurences, the vulnerability indexes obtained and their areal distribution, according to the water level depths. The Cristaline Basement representation is defined in a synthetic way, by 3 different domains, bearing in mind the 3 parameters already described, and also the degree of fissuring.

The comparison between the depth to the water table and the lithologies defines the vulnerability index in sedimentary aquifers. In general, São Paulo aquifers showed depths to the water-table at mean values of 10 to 20m, exceptionally reaching depths higher than 100m at the Bauru Group sediments. The aquiperm/aquitards lithologies which showed to be the less resistant to a given pollution load are found at the units Botucatu Caçapava, Caiuá and overlying cenozoic sediments.

Evaluating the overall vulnerability of the Paraná Sedimentary Basin aquifer units, the State of São Paulo major area is composed by superficial aquifers of moderate (either high and low) vulnerability. The highest indexes belongs to the Botucatu Aquifer, which also have the highest percentage of vulnerable areas, 20% Hh and 35% Hl. On the other hand, Passa Dois Unint shows indexes smaller than Lh (80%) and Hl (20%).

For the Cristalline Basement area, three domains were distinguished, by areas of water wells concentration and outcrop lithologies.

TABLE 1 Contaminant Load Generation Potencial: Classification Criteria

C.L.G.P. (*1) / Activities	High	Medium	Low
INDUSTRIAL ACTIVITIES	- proved contamination episode - hazard raw materials or products > 1 t/d - industrial liquids effluents infiltration in high quantities	- hazard raw materials or products < 1 t/d - industrial liquid effluents infiltration in small quantities - domestic liquid wastes infiltration of industries with > 300 workers	- industrial and domestic liquid effluents discharged into sewage - domestic liquid effluents infiltration of industries < 300 workers
SOLID WASTES	- proved contamination episode - use of hazard raw materials or products > 1 t/d (*2) - inappropriate final disposal of: - class 1 residues (*3)) 1t/month - class 2 > 100 t/month	-use of hazard raw materials or products < 1t/d -inappropriate final disposal of: - class 1 residue (1 t/month - class 2 residues (100t/month	- appropriate final disposal techniques - residues class III
EFFLUENTS LAGOONS	- effluents containing hazardous materials - non-hazardous materials, but lagoons > 1 ha (*4)	- hazardous materials are absent and - 1 ha > lagoons > 0.1 ha	- hazardous materials are absent and lagoons < 0.1 ha
MINING ACTIVITIES	- generate hazardous effluents in waste material or use hazardous substances and - inadaquate final disposal - residue is not hazardous but - sorrounding area is sensitive interns of pollution load generation and - 5% of the total municipal area used for minig	- generate/use hazardous materials and - adequate final disposal	- non hazardous materials are used and - sorrounding area is not sensitive and - < 5% of the total municipal area
URBAN RESIDENTIAL AREAS	- generate NO_3-N > 50.000 kg/a "in situ" disposition (*6)	- generate NO_3-N < 50.000 and > 30.000 kg/a "in situ" disposition	- generate NO_3-N < 30.000 kg/a "in situ" disposition

(*1) C.L.G.P. - Contaminant Load Generation Potential

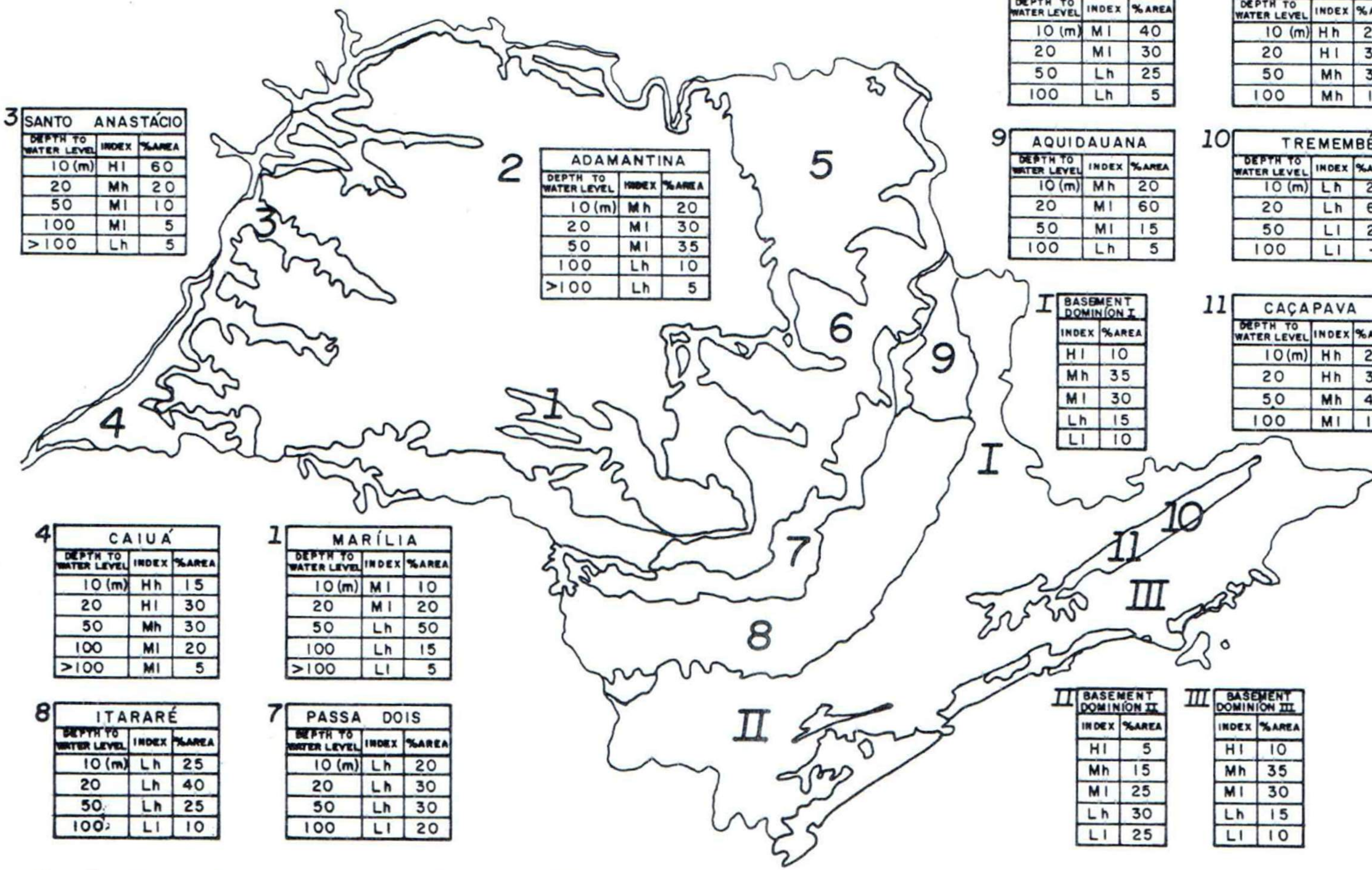
(*2) associat with industrial plant

(*3) class 1 hazardous material; class 2 soluble material; class 3 inert material (ABNT)

(*4) in case of non - existance of effluent lagoons, consider the results already obtained

(*5) includes industrial districts; Agro-industrial areas; possibility of receiving amount of domestic solid wastes significative

(*6) no considerated other activities (gasoline stations, vehicle workshops, service industries) and population density



3 SANTO ANASTÁCIO

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	HI	60
20	Mh	20
50	MI	10
100	MI	5
>100	Lh	5

2 ADAMANTINA

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Mh	20
20	MI	30
50	MI	35
100	Lh	10
>100	Lh	5

5 SERRA GERAL

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	MI	40
20	MI	30
50	Lh	25
100	Lh	5

6 BOTUCATU

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Hh	20
20	HI	35
50	Mh	35
100	Mh	10

9 AQUIDAUANA

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Mh	20
20	MI	60
50	MI	15
100	Lh	5

10 TREMEMBÉ

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Lh	20
20	Lh	60
50	LI	20
100	LI	—

I BASEMENT DOMINION I

INDEX	%AREA
HI	10
Mh	35
MI	30
Lh	15
LI	10

11 CAÇAPAVA

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Hh	20
20	Hh	30
50	Mh	40
100	MI	10

4 CAIUÁ

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Hh	15
20	HI	30
50	Mh	30
100	MI	20
>100	MI	5

1 MARÍLIA

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	MI	10
20	MI	20
50	Lh	50
100	Lh	15
>100	LI	5

8 ITARARÉ

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Lh	25
20	Lh	40
50	Lh	25
100	LI	10

7 PASSA DOIS

DEPTH TO WATER LEVEL	INDEX	%AREA
10 (m)	Lh	20
20	Lh	30
50	Lh	30
100	LI	20

II BASEMENT DOMINION II

INDEX	%AREA
HI	5
Mh	15
MI	25
Lh	30
LI	25

III BASEMENT DOMINION III

INDEX	%AREA
HI	10
Mh	35
MI	30
Lh	15
LI	10

Fig. 3 - Resume of the principal aquifer occurrences, the vulnerability indexes obtained and their areal distribution.

The domain no. 2, which is represented by granite-type composition rocks cutted by varions expressive strike-slip faults (Jundiuvira, Itú, Taxaquara and Pirapora faults) shows the highest vulnerability indexes (10% Hl and 45% Mh). The domain 3, composed predominantly of metassediments, shows smaller vulnerability indexes (65% of Lh and Lh), as a result of the relative ductil character of the lithologies, compared to the granitoids, although having thicker altered soils.

Potential Contaminant Load Cartography

For this project, 525 industries, 404 cities and 62 mining activities of interest were recorded and evaluated, from an approximate total of 24000 industries and 572 cities of the State of São Paulo. Considerations are made as to the domestic solid wastes disposal and generation, although not included in this work once they are still not concluded.

Industrial solid wastes were assessed as part of the industrial activity, once its disposition is made, in many cases, inside the plants limits.

The potential loads classification, in terms of hazards to groundwater, are based on Hirata and Bastos (1990) and also presented in this seminar by Bastos et al. (1990).

The potential contaminant load, evaluated as to the domestic sewerage (in situ disposed in to the soil), industries (including hazardous residues generation) and mines, is syinthetically represented in Fig. 4. In this illustration, the amount of activities are presented according to their classification as high, moderate and low. It is worthwhile to remember that an activity should not be compared to another in terms of its classification. Therefore, a highly risky mine does not indicate that this activity is more dangerous to the groundwaters than a moderate risk industry.

In terms of industrial activities, the Campinas Administrative Region (5) is the most worrying one. From the 139 industries recorded, 68 showed high and 38 moderate potential load risk. The chemical industry, followed by sugar and alcohol plants using infiltration of their effluents in the soil, and food and leather tanning were the ones who composing the group classified as of high potential contaminant load.

The Administrative Region 6, Ribeirão Preto, present an expressive industrial park, with a total number higher than 6000 facilities. The project distinguished 135 of them interesting to groundwater, from which 41 were classified of high and 30 moderate potential. Having an industrial conglomerate as diversified as that of Campinas, the industries of highest generating potential are sugar and alcohol usines and leather tannings.

As to the sanitation condition, the State of São Paulo presents satisfactory services indexes. The region that most utilizes in-situ sanitation systems is Campinas, followed by Sorocaba. In Campinas region 18 cities were classified as high and moderade potential load generation, and at Sorocaba, 20.

Mining activities comprehends majorly civil construction material extraction, not involving hazadours materials in the minerals processing or in wastes. The most important factor of preocupation in relation to grounwater is associated with the sorrounding activities, once the over burdened retrieval increases the vulnerability, exposing the water table to the atmospher in many instances. Only 17 mines that exploit substances offering some risk make part of the record. In this group are included gold, cooper, coal, nickel, phosphatic rocks mines, among others. These activities are concentrated in the Ribeira Valley and Sorocaba.

Agriculture practices were not included in this report, once the recording is not yet finished.

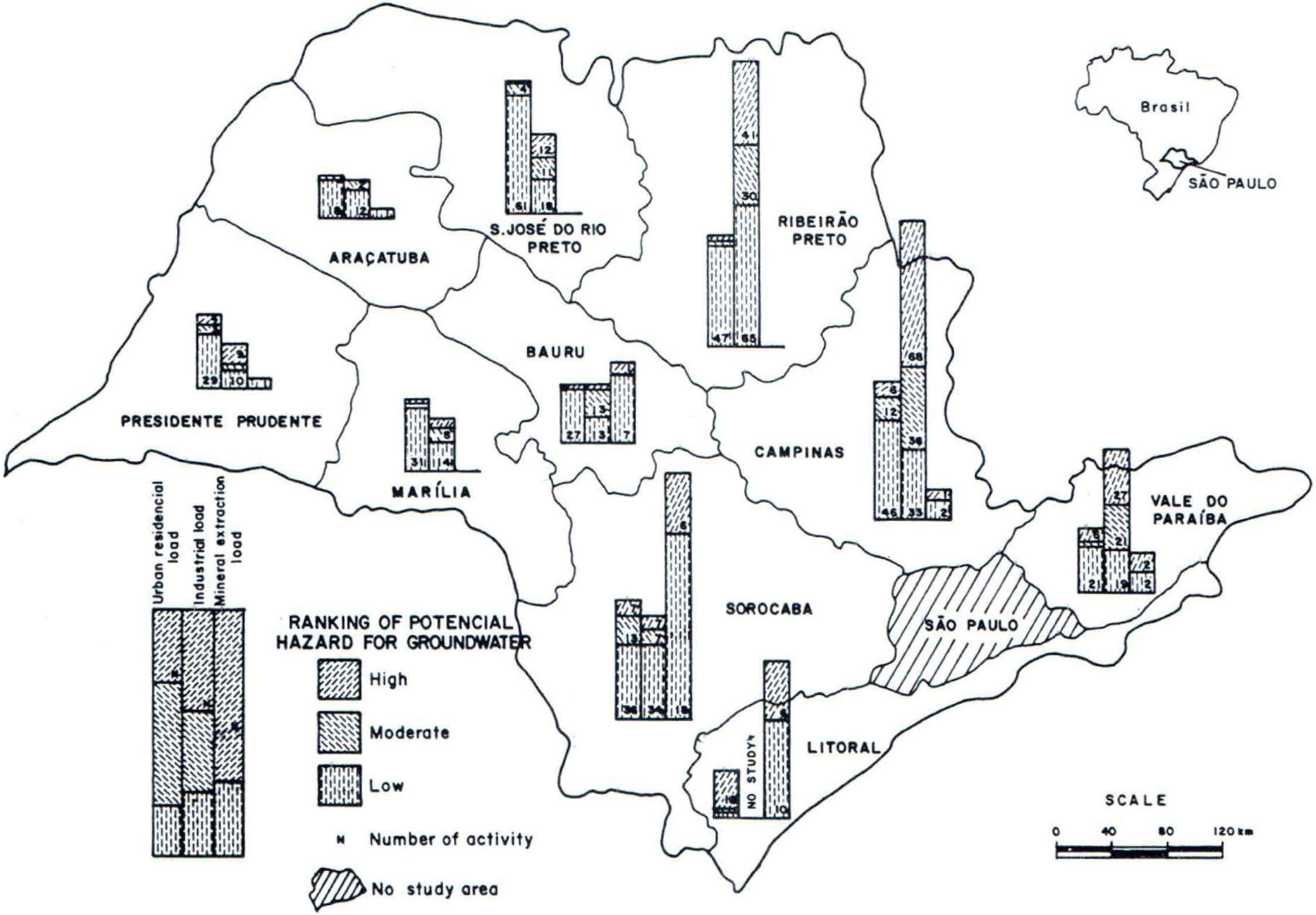


Fig. 4 – The potential contaminant load evaluated to the unsewered sanitation (domestic in situ disposal load), industries and mines.

CRITICAL AREAS

While applying the concepts of groundwater pollution risk (Fig. 1), defines the areas of groundwater pollution risk. In such a definition, it was considered that when an activity utilizes hazadours, mobile and persistents pollutants, the area would be classified as of high risk.

As the works are not concluedyet, it was not possible to define all of the critical areas of the State; however, for a preliminary evaluation, 4 large zones (area concentrations) of risk can be identified: the city of Ribeirão Preto and sorroundings (outcropping area of the Botucatu Aquifer, associated to intensive industrial activity, of occupation and aquifer exploitation); the Paraiba Valley region involving the cities of São José dos Campos, Taubaté and Pindamonhangaba (outcrop area of Caçapava Aquifer with mechanical engeneering, metal processing and chemical industrial activities); the city of Franca (cenozoic sediments and intensive leather tanning), and Campinas Region (industries of high polluting potential in a moderate vulnerable geological framework).

The outcrop area of the Botucatu and Pirambóia formations, being this the most important aquifer of the State and the one with the highest vulnerability indexes, has shown to be a zone of high environmental preocupation, most of all because of the convergent character of an industrial axial growth towards its direction: the Campinas-Ribeirão Preto axis.

CONCLUSION

The most logical approach to the definition of groundwater pollution risk is to conceive it as the interaction between the contaminant load and the aquifer pollution vulnerability.

In the State of São Paulo, the vulnerability map, in 1:500.000 scale, distinguished, in basis of 31 aquifer units, areas with 6 level of vulnerability index. The evaluation concluded that major areas of its territory ares composed by superficial aquifers of moderate (either high and low) vulnerability. The highest indexs belongs to the Botucatu Aquifer, which also have the highest porcentage of vulnerable areas, 20% Hh (High-high index) and 35 Hl. On the other hand, Passa Dois Unit showes indexes smaller than Lh (Low-high, 80%) and Ll.

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In terms of the industial activities, the chemical industry, followed by sugar and alcohol plants using infiltration of their effluents in the soil and food and leather tanning were the ones who compose, in general, the group classified as of high contaminant load generation.

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The mining activities comprehend majorly civil construction materials extraction, not involving hazardous susbtance in the mineral processing or at the waste. Only 17 mines that exploit metalic materials offer direct risk.

As the works are not yet concluded, it was not possible to define all critical areas of the State, for a preliminary evaluation however, four large zones (areas concentration) of risk can be identified: the city of Ribeirão Preto, part of Vale do Paraiba region, the city of Franca and the city and the region of Campinas.

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