Aqua Bavaria Guarani

Joint Venture of German Consultants for the sustainable development of the Guarani Aquifer

The Management of Aquifers

An Example of an Integrated Solution for the Creation of Potable Water Protection Areas with the Use of Sustainability Computations and Advanced IT Support Systems

by COPLAN AG

DORSCH CONSULT

Geotechnical Consultants

HYDROISOTOP GmbH

IT & More

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Contents

1. Preface

The Secretaria de Estado do Meio Ambiente São Paulo and the Bavarian State Ministry of the Environment, Public Health and Consumer Protection can proudly look back on a long period of mutual cooperation which originates from the signing of the first „Letter of Intent“ in 1997. The technical cooperation was then given a specific direction when a new agreement was signed in May 1999 to extend the transfer of knowledge to the fields of

- Bavarian water resources management administration
- groundwater management and
- drinking water protection

Action soon followed the written word.

In July 2001 the Secretaria do Meio Ambiente do Estado de São Paulo proposed a concrete project of cooperation for specialists from São Paulo and Bavaria. The project: „**Information System for Groundwater Resources Environmental Management in the Outcrop of the Guarani Aquifer in the Sao Paulo State**“ aimed at showing protective measures for the „Guarani Aquifer“ and developing a sustainable utilization of this valuable groundwater resource for coming generations.

Experts from São Paulo and Bavaria discussed in seminars, workshops und roundtable meetings the essentials and worked out the main fields of investigation and activities necessary for the “Guarani Aquifer Project”:

- transparent determination of groundwater recharge
- professional and administrative development of groundwater and drinking water protection
- development of a database for groundwater management

Coordination on the Bavaria side was carried out by “Project Water Technology Transfer” (TTW). TTW was developed on behalf of the Bavarian State Ministry of the Environment, Public Health and Consumer Protection and its concept is based essentially on conclusions of the “Agenda 21”, in particular with respect to integrated water resource management. It aims to assist international cooperation in the water management sector and acts as a stepping stone in Bavarian efforts to promote technology transfer. Moreover, the Bavarian water management administration is able to effectively support export trade with help from this water management network. A further objective is the transfer of environmental technologies and the support of Bavarian companies - especially small and medium enterprises - on the world market of water management. However, the most important concern for TTW is the implementation of the "Agenda 21" objectives to guarantee the sustainable use of natural resources.

The participants in this project were from Bavaria:

- **IT & More** - Gesellschaft für Projekt- und Organisationsberatung – Datenbankentwicklungen München
- **Fachbüro für Hydrogeologie und Geotechnik** - Prof. Dr. Schuler - Dr. Ing. Gödecke - Augsburg
- **Hydroisotop** - Fachbüro für Hydrochemie, Isotopenhydrologie und Hydrogeologie Schweitenkirchen
- **COPLAN AG,** Eggenfelden

from São Paulo:

- CETESP
- Instituto Geológico.

Professor Hans Frisch, former expert at the Bavarian Water Management Agency, was in charge of specialist coordination for the Bavarian administration, whilst **Professor Uwe Tröger** from the office of **COPLAN AG** coordinated the Bavarian engineering contributions. The Free State of Bavaria and the São Paulo State divided the costs. The Bavarian financial support was used for Bavarian engineering expertise in São Paulo.

Throughout all its working phases, the project was followed with great interest and supported by the environment ministers of both states, **Professor Goldemberg** and **Dr. Schnappauf**. The project has now been completed and was very successful.

In the following pages the Bavarian participants present the results of their work.

Erich Eichenseer - TTW Adviser

2. Aims of the Project and Summary

The project followed up three essential aims which were coordinated with the partners in São Paulo. The design of a database which builds up on a GIS (geographical information system), the exemplary delimitation of drinking water protection area at three wells in Ribeirão Preto on the basis of Bavarian water legislation, and the calculation of groundwater recharge for the region in order to understand the groundwater flow and to upgrade groundwater management.

Groundwater protection areas: Water legislation in the state of São Paulo includes the delimitation of drinking water protection areas. The definition of the limits is only clearly given for the well itself. A procedural regulation should be found which facilitates the delimitation of drinking water protection areas by technicians. The exemplary representation of the reserves at three wells in Ribeirão Preto has made it clear that the Bavarian method can only be carried out by hydro-geologists. It also has become evident that an adaptation of the regulation to conditions in the of state of São Paulo is necessary.

Groundwater recharge: The water balance was calculated using a new method which particularly takes into account the soil and the topography. The model called REGIS was successfully used in the North-East of Brazil. The calibration was carried out by the evaluation of isotope data. The calculated model indicates regional values and shows a clear distribution of the groundwater recharge. The analysis of isotopes clearly showed that a less however significant groundwater recharge takes place in the basalt of Serra Geral formation. With further monitoring a very good groundwater management can be operated.

Data base: This system is needed for data management and for all authorization concerning groundwater project approval in the state of São Paulo. Apart from users in the administration authorities, selected data should also be accessible to a public. A database which could be connected to a publicly accessible GIS (public domain) was designed successfully. All entered data are checked for their plausibility, and the authorities are able to protect particular data from access by unauthorized employees or the public. To reach the highest possible flexibility for the database, the methodology of Entity Relationship Modelling was used with an unlimited capacity for data and data check.

3. Partners Involved

The Aqua Bavaria Guarani is a joint venture of highly specialized companies. Due to this conjunction ABG is able to cover all the knowledge that is necessary to maintain (large) aquifer systems respecting a high standard of sustainability. Additionally our strategy in international projects is to cooperate with local partners with their specific knowledge about regional structures and problems.

Homepage: http://www.abg-guarani.de/

3.1 COPLAN AG

COPLAN AG is an independent consulting and engineering company headquartered in the state of Bavaria in Germany and specialized in the areas of building design and construction, structural, mechanical, electrical as well as civil and infrastructure engineering services. The company was founded in 1963. Our head office is in Eggenfelden with branches and suboffices in Munich, Berlin, Passau, Weiden, Erding and Straubing. Our staff consists of 120 members, 2/3 of which own COPLAN shares. Annual turnover of our company is about € 7 million.

COPLAN AG is a supplier of top-rate engineering services. Taking an interdisciplinary and holistic approach, we are in a position to act as consultants in projects on minor scale as well as master planners on major scale. Our clients are sited in Germany and abroad, including public and industrial clients of individual structure and size. Our experience and expertise in methods of project planning ensure that we proceed with efficiency until each project is completed.

In line with the demands of today’s market, COPLAN continuously trains it’s staff in professional as well as in soft skills. Keeping pace with the newest techniques and the development of operative methods are the basis of our work. We maintain our standards by a quality management system certified according to DIN-ISO 9001-2000.

3.2 DORSCH CONSULT

The company was originally founded in 1950 and ranks today as one of the largest consulting engineering companies in Germany. Its foreign activities commenced in 1956. The share capital amounts to € 8 million, with annual fees of the entire Dorsch Group totalling some € 85 million.

These fees are earned by a staff of 1,400 permanent employees including 1,000 professionals who represent the true capital value of the company. Staff participation in interdisciplinary teams coupled with experience gained from projects in more than 110 countries in four continents ensures continuous thrusts of innovation.

Dorsch Consult handles about 300 projects each year and serves both public agencies and private enterprises. In Germany the clients are municipal and state and federal authorities, and industrial establishments. Overseas, across all five continents, the clients also include governments and government agencies.

3.3 Geotechnical Consultants

Geotechnical Consultants
Prof. Schuler & Dr. Gödecke

The Geotechnical Consultants in Augsburg, founded in 1986, are an expert team of geologists and civil engineers under the leadership of Prof. Dr.G.Schuler and Dr.-Ing. H.J.Gödecke, working in the fields of hydrogeology, engineering geology, soil mechanics and foundation engineering as well as on environmental tasks.

The specialized hydro-geologic activities are groundwater exploration and balancing of groundwater resources, groundwater management and delimitation of drinking water protection areas, conceptual and numerical groundwater modelling, design and sanitation of waste deposits, investigation and sanitation of soil and groundwater pollutions.

The annual turnover is about € 1,5 million with 60 to 80 projects. Besides the activities in Germany, projects are located in EU countries, in the Far and Middle East, Africa and Brazil.

3.4 HYDROISOTOP GmbH

Hydroisotop GmbH is an environmental, hydrologic and hydro-geologic consultant office. Hydroisotop GmbH has profound experience in the field of measurement and interpretation of isotope data and water quality data.

During the last 20 years the company focused on water research and specialized in the measurement and interpretation of natural isotope data in connection with chemical investigations to determine groundwater age, to investigate groundwater resources and to define the origin of contamination and pollutants.

Hydroisotop has now been working for more than a decade in international cooperation projects. In Northern Brazil, Ceará and Piauí, Hydroisotop worked on the planning of water resources and water quality investigations within a BMBF and CNPQ funded project from 1993 to 2001. Within this project, integrated water management tools and Decision Support Systems on water quality management and water-born diseases have been developed and made available for further application.

3.5 IT & More

IT & More is an independent company which produces and adjusts software according to individual demand. The company has extensive experience especially in engineering software solutions supported by data bases. Our internationally proven ability to integrate differing needs allows us to act within heterogeneous groups. Among other areas, our expertise includes the development of operational business systems, data migration, (geographical) management information systems, data warehouse solutions. Our projects range from complex environmental technology to everyday business solutions, whilst our proficiency in software engineering and project management encompasses the entire life cycle of software from problem analysis, via conceptual models, programming, implementation and maintenance during the process of production.

CyProtect, a 100 % subsidiary of IT & More offers a wide range of knowledge in data processing security in networks including internet.

4. Drinking Water Protection Areas

4.1 The Importance of Groundwater Protection and Installation of Drinking Water Protection Areas

Water is the basis of all life on our earth. Groundwater, by its nature and genesis, is the best drinking water we have and has to be regarded as a treasure given to us. But it is exposed to many risks of pollution by activities in agricultural, horticultural, forestry and industrial land use as well as by urban settlements, in particular as a result of leaking sewers, waste deposits, waste water plants and traffic routes. Groundwater protection is thus a crucial issue and sustainable regulations are necessary to guarantee a secure public water supply and to maintain and, if necessary, to improve the groundwater quality. For this purpose drinking water protection areas are defined in order

- to prevent contamination by substances and organisms hazardous to human health,
- to prevent contamination by substances and organisms, which may not be hazardous to human health, but may affect water quality.

The basis of the delimitation of drinking water protection areas are the hydro-geological conditions of the catchment areas of the production wells to be protected.

4.2 General View of the Guarani Aquifer System in the Region of Ribeirão Preto

The eastern part of the urbanized area of Ribeirão Preto is located in the outcrop area of the Guarani Aquifer. The aquifer consists of fine to medium grained sandstone beds of the Triassic-Jurassic Pirambóia Formation (TJp) and the Jurassic-Lower Cretaceous Botucatu Formation (KJb) (see annex 2), geologic map according to SINELLI (1973). The eolian-fluvio-lacustrine sandstones of both formations show a total thickness up to about 200 – 250 m and are locally covered by sandy to silty sediments of Cenozoic age (Cs) with a thickness up to 30 m. The sandstones are partly interbedded by Mesozoic intrusions of diabase (KJs). In the western part of the urbanized area the Botucatu sandstone is covered by basalt of the Serra Geral Formation (KJsg) of Jurassic to Lower Cretaceous age reaching a thickness of more than 100 m. The Botucatu sandstones, which represent the upper part of the Guarani Aquifer, show a lower silt and clay content than the Pirambóia sandstones below.

Faults, joints and fractures of the sandstones and the basalts stretch mainly in north-eastern and north-western directions (annex 3). Therefore the chosen pathways of groundwater flow are presumed in these directions. Horizontal cracks seem to play an important part in the water flow too. Annex 2 shows a relevant contour map of the static head of the GAS elaborated on the basis of measurements done between 1997 and 2002. There is a prominent groundwater divide in the eastern part of the urbanized area and a distinct depression in the western part caused by groundwater exploitation over some decades. This divide and this depression are the dominant features mainly influencing the flow pattern of the aquifer. The recent lowering of the static head was found 1.2 m on average per year.

In the eastern outcrop area the Guarani head is unconfined, whereas in the western area it is mostly confined due to the overlying aquifer system of the Serra Geral basalts. In the valleys of the Ribeirão Preto and other creeks the thickness of the groundwater cover of the GAS is for the most part less than 50 m, but in the areas covered by Serra Geral basalts it reaches more than 100 m (see annex 3).

FIPAI (1995) reported chemical analyses of 156 wells in Ribeirão Preto in the period between 1973 and 1995, essentially:

- Electric Conductivity 11 – 230 µS/cm, usually < 70 µS/cm,
- Chloride up to 20.5 mg/l, usually < 5 mg/l,
- Nitrogenous Nitrate (N) up to 17.5 mg/l, usually < 5 mg/l,
- Fluoride 0.03 – 2.00 mg/l, usually < 0.2 mg/l.

At present 96 active wells of the “Departamento de Água e Esgotos de Ribeirão Preto” (DAERP) produce drinking water for public water supply, 85 further DAERP wells are abandoned and additionally 79 private wells are registered extracting groundwater for various uses, some of them drinking water too. As far as we were told, installations to record continuously the amount of water extraction are not available, and declarations of the annual water consumption are based on summarizing momentary pumping rates of the wells. For this reason an amount of 103,680,000 m^3 per year, reported by CHANG (2001), has to be regarded with the reservation that it might be too high with respect to a resulting consumption of more than 500 l per inhabitant and day. Anyhow, considering the estimation of groundwater recharge presented in chapter 5 and continuous lowering of the water table mentioned above, there are indications that extraction might considerably exceed recharge.

4.3 Delimitation and Classification of Drinking Water Protection Areas According to German and Bavarian Standards

Drinking water protection areas should normally comprise the entire catchment area of the production wells and should be classified with respect to the risks caused by various activities and land use contributing to groundwater contamination. Furthermore, the type, location and duration of the activity as well as the thickness and permeability of the groundwater cover are important factors. Restrictions on land use in different zones of the protection area must reflect the risk potential, which normally decreases when the distance of the activities to the well increases. According to German and Bavarian standards and guidelines the protection areas of drinking water production wells usually are arranged in three zones. The prohibitions and restrictions of activities in these zones are listed in a catalogue (an extract is presented in annex 5).

Zone I (Well Protection Zone)

Should be extended over an area not less than 10 m x 10 m. It protects the well and its nearest surroundings against any pollution and should be fenced.

Zone II (Narrow Protection Zone)

Protects groundwater particularly against contamination by pathogenic microbiological constituents (such as bacteria, parasites and worm eggs) and other pollutants, which may be hazardous at a short distance from the well. This distance is normally represented by the 50 days flow distance to the well (50 days TOT-line). In cases of a very low vulnerability of the aquifer in the catchment area due to a high protective effectiveness of the groundwater cover, the formation of the protection area can, under exceptional circumstances, be set up without a Narrow Protection Zone.

Zone III (Wide Protection Zone)

Protects groundwater against contamination which affects water over long flow distances, such as pollutants from radioactive substances or chemicals, which are not degradable or not easily degradable. Protection Zone III may be divided into a Sub-Zone III A, adjoining

Zone II, and a more distant Sub-Zone III B. If there is no division into Sub-Zones, the restrictions and prohibitions concerning activities and land use in Zone III A are decisive for the entire Wide Protection Zone.

A diagram showing the administrative steps necessary for the procedure of declaration for a drinking water protection area in Bavaria is attached in annex 6.

4.4 Exemplary Delimitation of Protection Areas for Three Production Wells

The DAERP wells P 161, P 167 and P 176 outside the urbanized centre served as examples to elaborate arrangements of drinking water protection areas in Ribeirão Preto according to German and Bavarian standards and guidelines. The locations and the extent of the delimitated protection areas of these wells are shown in annex 4.

Decisive for the delimitation of the protection zones around the wells are the hydro-geological data, on the basis of which the extent of the catchment areas is estimated. In particular:

- the aquifer boundaries and the groundwater flow direction,
- the thickness and permeability of the groundwater cover,
- the width of the central flow to the well depending on the extraction rate, the transmissivity of the aquifer and the gradient of the water table (figure 1),
- the recharge rate and the extent of the recharge area required to compensate the amount of the well extraction.

With respect to dispersion of the groundwater flow and the inhomogeneity of the aquifer, the lateral extension of the central flow areas is performed with an angle of about 10^o to 12^o (figure 1). The 50 days TOT-lines delimiting the boundaries of the Narrow Protection Zone were calculated using simplified numeric models of the well regions.

With regard to low vulnerability of the GAS in the catchment area of well P 161 due to the thickness of the groundwater cover and additional protection by the overlying Serra Geral Aquifer (2875 points of total protective effectiveness according to the method of HÖLTING, 1995) the arrangement of a Narrow Protection Zone II was not considered necessary for this well.

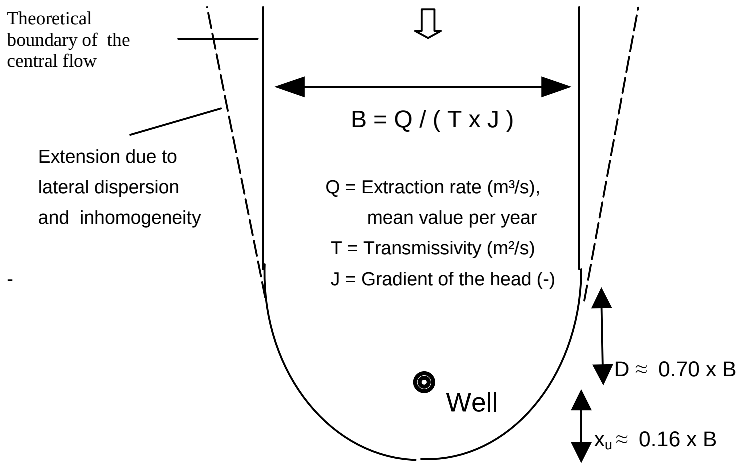

Figure 1: *Estimation of a well flow area*

In the catchment area of well P 176 a direct outcrop of Botucatu sandstones, causing a high vulnerability of the aquifer, is located near the upstream boundary of the Wide Protection Zone; therefore this zone was not divided into Sub-Zones III A and III B.

4.5 Conclusions

The exemplary demonstration of how to elaborate and to delimitate drinking water protection areas in Bavaria is deemed to be useful in non-urbanized areas or in areas with a lower population density and without the existence of extended industrial land use. However, considering the densely populated areas such as the urbanized centre of the city of Ribeirão Preto, a fully effective drinking water protection cannot be attained. In such regions feasible protection areas should be elaborated and set up, respecting already existent land use and including practicable restrictions to maintain the momentary situation in order to prevent a deterioration. A minimum requirement would be to at least prohibit the building or the enlargement of industrial plants or other objects producing or handling hazardous substances in order to stop infiltration of waste water wherever possible. Furthermore permission should not be given to install new wells in areas which cannot be protected effectively.

In less densely populated regions the Bavarian catalogue of restricted and prohibited activities and land use in drinking water protection areas - attached as an extract in annex 5

- could be a basis to define a Brazilian catalogue taking the local conditions, acceptance and possibilities into account. This should occur after a thorough discussion with all the appropriate authorities involved in groundwater protection. In order to avoid an increase in the content of nitrate and plant protecting substances in areas of intensive agricultural land use, public water suppliers in Bavaria usually enter into contracts with the farmers so that fertilizing takes place with respect to the right time and according to the demand of the plants. Such restricted fertilization causes a certain decrease in agrarian productiveness; the farmers therefore receive compensatory payments from the suppliers.

Regarding the fact that there are indications in Ribeirão Preto of exploiting more groundwater than is replenished, it has to be pointed out that protecting groundwater must not only respect qualitative but also quantitative aspects. New exploitation areas outside the urbanized area and, as far as possible, outside the recharge areas of wells already extracting water at present (annex 9) should be explored and provided with priority for drinking water production by law to enable the installation of effective protection areas. Wells with a high degree of contamination risk (annex 3) should be abandoned at first and transferred to new exploitation areas.

5. Groundwater Balance

5.1 Establishing Groundwater Balances

An extensive literature review was carried out listing the available studies on groundwater balance estimations in Brazil. These studies have been compiled in a database, analyzed and summarized. Based on the literature review the best method for the estimation of recharge in Ribeirao Preto within the pilot study was chosen. The choice of methods took into account several aspects that were considered in the survey of existing methods, among them (1) data availability, (2) purpose of the study, (3) time and spatial scale of the basin, (4) costs and infrastructure. The soil water balance approach is considered suitable for local and meso-scale studies (up to a few hundred km²). It was found that data availability is good enough for the application of distributed balance models in many places in the State of Sao Paulo. Isotope studies have been identified as an important tool for the estimation and validation of recharge and development of conceptual models also on a regional scale.

In order to establish a quantitative water balance for the study area, a water balance model was developed. The hydrological processes have been simulated with a recent version of the water balance model REGIS. The model calculates interception losses, runoff generation, infiltration, soil moisture storage, interflow, evaporation and groundwater recharge on a daily basis. For the model REGIS all the time series data (meteorology) and spatial data sets have been prepared (topography, land-use / vegetation, effective field capacity, hydraulic conductivity and sub-soil conductivity) jointly with experts from CETESP and Instituto Geologico and Instituto Florestal.

The model permitted a visualization of the processes and the temporal distribution of recharge. During the rainy season, soil water storage increases until the field capacity is exceeded. This results in an increased vertical soil water flux and a net groundwater recharge that peaks in December, January or February – depending on the actual meteorological conditions.

A recharge map for the study area as a whole has been prepared. Higher recharge rates are observed where the soil texture is sandy and where land-use with shallow root depth prevails.

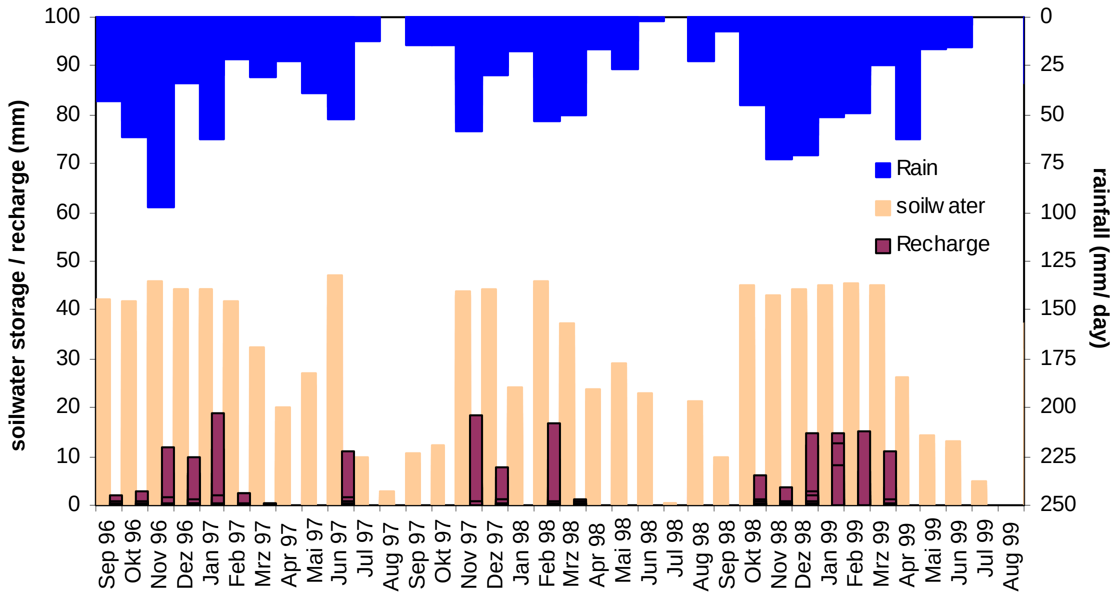

Figure 2: *Typical recharge distribution in the study area Ribeirao Preto*

Groundwater recharge is highest in the area covered by unconsolidated Cenozoic sands, and in the outcrop area of the Botocatu Formation.

The results show that, in spite of high rainfall amounts, recharge is comparatively low due to the fact the rain falls during the warm summer and evaporation is high. A major part of the rainfall of 1413.27 mm/y evaporates and is used for transpiration. The total actual evaporation figures corresponded well with existing data (about 1050 mm/y). Recharge ranges from about 200 to 250 mm/y in highly permeable areas, mainly outcrops of the

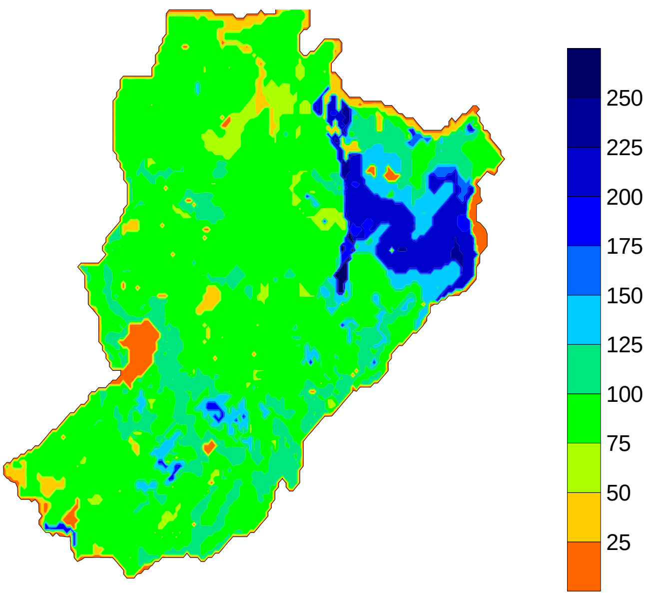

Figure 3: *Recharge map of the study area (September 1996 to August 1997) in mm/y*

Botocatu Frm. and unconsolidated Cenozoic sands, down to 50 to 100 mm/y in the area where the Botocatu aquifer is confined by the basalts of the Serra Geral Frm.

5.2 Isotope Investigations

Isotope investigations have been carried out as a follow up of isotopes by GALLO & SINELLI (1980) in the study area. The isotope study was made to get more information on recharge processes and on groundwater ages that allow a verification of estimated groundwater recharge rates. The stable isotope composition (^{18}O and deuterium) of groundwater corresponds to the composition of the rainfall during the months with the highest recharge (January, February). The presence of tritium in two samples close to the outcrop area of the Botocatu shows that the system is being actively recharged. The absence of tritium in the other samples mainly taken from boreholes with confining Serra Geral Formation (Basalt, Diabase) constrained the proportion of groundwater that is contributing to the Botocatu Formation to less than 100 mm/y.

5.3 Conclusions

The recharge estimation facilitates achieving a balance between abstraction and recharge. This is a prerequisite for a long term sustainable use of the Guarani Aquifer. The recharge rates of between 70 and 250 mm/y are due to the coincidence of high rainfall with high temperatures and high storage capacities of the soils. More information is needed to understand the complicated flow patterns in the Guarani Aquifer. Isotope studies have proven to be very useful in this regard, especially age indicators along flow path profiles (^{14}C, industrial gases). Monitoring activities on groundwater level time series, abstracted amounts of groundwater and on indicators for the evolution of the groundwater quality (agrochemicals) should be continued. The results can be used to establish a quantitative and qualitative groundwater management. The availability of groundwater can be estimated dynamically on different scales. Using the model, the impact of land-use changes and climate changes on the availability of groundwater can be predicted.

5.4 Verification and Catchment Balance

In order to consider the plausibility of the total recharge rates presented above, to estimate the effective i.e. usable recharge of the GAS in Ribeirão Preto and to prepare a water balance of the catchment area of the groundwater extracting wells, a simplified numeric flow model using Modflow was set up. Annex 9 shows zones of different effective recharge in the catchment area taking groundwater and surface water divides into account: an unconfined aquifer zone of direct recharge in the eastern outcrop area (REC-D, 100 km²) and a confined zone of leakage recharge (REC-L, 290 km²), subdivided into an urbanized area (REC-Lurb, 140 km²) and an outside area with a sparse settlement of population (REC-Lout, 150 km²).

The western and southern borderlines of the model are fixed head and partially no flow boundaries, whereas the eastern boundary representing the groundwater divide is not fixed. The northern border is represented by the River Pardo. The aquifer conditions alternate between confined and unconfined. The aim of modelling was not to create contours very close to those shown in annex 2, but to simulate the eastern divide by reaching a contour of 550 m above sea level and to simulate the western depression producing a contour of 440 m a.s.l. when varying the hydraulic data and especially the recharge in the different zones within a plausible range. The inflow coming from outside into the model area and representing the replenishment of the sparsely populated region (figure 4) should result in a recharge rate being higher than that of the urbanized area. In annex 10 a list of the final stage of the model runs is presented. It can be seen that the runs showing the most plausible results were produced with an effective direct recharge in the outcrop area of about 150 mm per year (4.5 to 5.0 l/ s x km²) and an effective leakage replenishment of about 45 mm per year (1.35 to 1.50 l/s x km²) in the urbanized area, leading to an inflow, which is in conformity with a recharge rate of approximately 60 mm per year (1.8 to 2.0 l/s x km²) in the thinly peopled region.

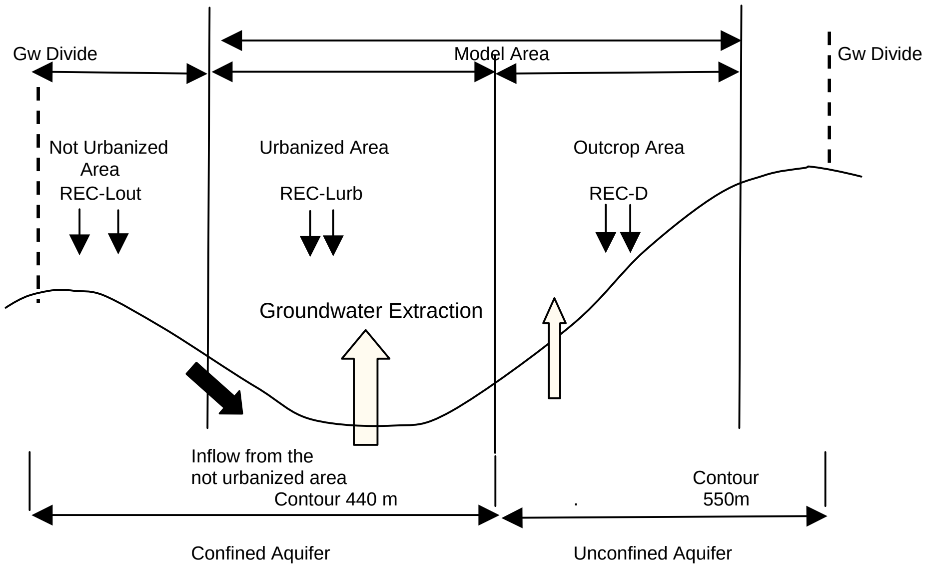

Figure 4: *Schematized cross section of the model region*

The water balance of the total catchment area can be seen in annex 11, resulting in an effective replenishment of the GAS of about 1000 l/s (3600 m³/h respectively 31.500.000 m³/year).

6. Geographic Information System

At the beginning of developing the information system, the situation was as follows:

- Various institutions provided us with their collections of datasets for the project. It was not planned to create a means for data collection, but it became clear that a manual correction of the existing data was essential.
- The format of these datasets was also very heterogeneous. Some of them were already available as data bases, others as Excel, Word etc., and some only on paper.
- Some of these datasets contained information about the same existent objects, but not necessarily the same information - neither in content nor in structure. In fact a high variety of semantics and contradictory content had to be treated.
- For the pilot character the project concentrated on producing the highest possible quality of data to support an exemplary analysis by hydro-geologists. In contrast to this the technical equipment was secondary.

On basis of these facts, the workflow of software engineering was organized in three steps:

- Analysis and creation of the structure of the information pool
- Integration of the existing data into a new data base
- Usage of reasonable tools for querying and analysis, and the integration of standard-GIS-tools

6.1 The Analysis of Demands

A detailed analysis of the information was reached by discussing the use cases of the (hydro-geological) working procedure of end users. The first goal was to create a static information model that could serve as an information pool to be consulted directly by analysts or by interfaces to third-party tools. Since the static character of the model was the foremost consideration, it was decided to use the methodology of Entity Relationship Modeling (result see annex 12). The advantage of this methodology is sophisticated formal consistency checks of the data model which is very well suited to creating information structures of high quality.

The ability of the ERM was finally checked against the workflow of use cases. This defined set provides a minimum of usability of the system, although the capacity is not limited to it. The main use cases being discussed are:

- Implementation of protection areas respectively of new groundwater exploration areas
- Calculation of water balance
- Quality and quantity monitoring
- Reaction to accidents
- Licensing and inspection for enterprises

The step was completed by the definition of the plausibility checks being necessary to guarantee a high quality level of data.

6.2 The Physical Basis of Data

Within the next step, technical solutions for the synchronisation of all the heterogeneous data were to be implemented. The main idea was to divide the information pool into three layers. Layer 1 represents the storage of each incoming data in a structure that is already adjusted to the semantics of the new information pool. The supporting technique was chosen as XML-based "states in between" that finally allow the storage in the targeted structures of a Relational Data Base. Layer 2 is derived from layer 1 by synchronizing potentially contradictory information into a "unique reality"; this includes a manual correction. Finally layer 3 is the excerpt of high quality data which is provided to end users for analysis. Data on this level has passed all quality checks and synchronisations. Additionally this level may contain filters according to the rights of access to data.

The architecture of the named three layers was implemented in physical structures of a Relational Data Base using MS SQL. The physical layers 2 and 3 represent the ERM in a fully normalized form, level 1 allows offences against the referential integrity. The import and maintenance tool-set is individually programmed in Visual Basic.

Additionally an important set of thematic maps was compiled as shape files by a specialised team in CETESB. This includes about 35 maps e.g. topographic maps, hydric resources, groundwater vulnerability, potentiometric maps, administrative regions, roadways, favelas, industrial zones, land use, protection zones and areas, contaminated areas, environmental accidents and others.

6.3 Analysis Tools for End Users

The tool-set provided to the end user is a compilation of individually programmed dialogs in Visual Basic and standard tools made by ESRI. For a wide spread clientele ESRI's Arc-Explorer as freeware was chosen to do "everyday analysis".

For more advanced users ArcView[1] applications are provided. Both tools are integrated into the system by the creation of functionality adapters, that allow the connection between the standard tools and the tailor-made components in Visual Basic. In this way both points of view for accessing data are available: The standard view on data in a GIS-system is extended to the more data base oriented view of navigating in tables. Of particular importance is the subsequent "drop down" information detailing as given by the ERM:

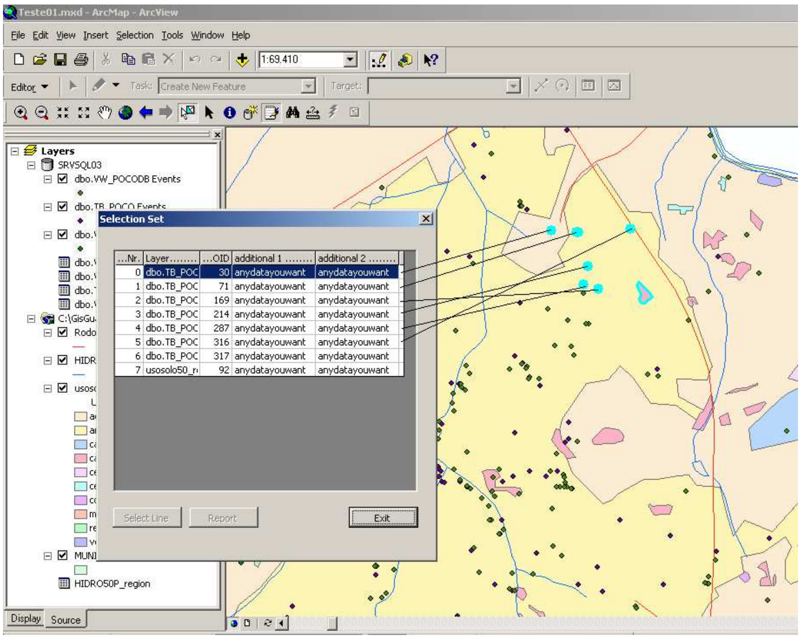

Figure 5: *Adapter between ArcView and Visual Basic*

The GIS enables locating the entry-point - e.g. a specific selection of wells - in an intuitive way by pointing with the mouse on a map, but does not permit following the information tree e.g. to a series of pumping tests and the related values. The second step is supported by Visual Basic applications tailor-made for that purpose. The link between the standard tool ArcView and the tailor-made solution is implemented by using ArcObjects / Visual Basic programming. To the end user the bridge is absolutely transparent - there is no break of the medium. The list of the selected features is invoked by a click to the toolbar. (For another sample see annex 13).

[1] ArcView and ArcObjects are products of ESRI, California

7. Conclusions and Future Applications

The project has been a pilot study demonstrating some key elements and methods of groundwater water resources management: information technology – integrated data analysis – specific models for decision support. Valuable conclusions regarding future application can be drawn from the project. Information technology is a central element for resources management. A pilot database and information system has been developed, demonstrating the benefit of systematic environmental data management. The management of data is the basis for the application of methods and evaluation tools.

The methodological approach of software engineering by modelling the contents according to the needs of the workflow is the basis for the adaptability and the scalability of the information system in specific environs. Therefore a further detailing of the created entities as well as the integration of new subjects, such as waste treatment or the management of superficial water, can easily be done. The technical solution is given either by extending the data base or by a semantic synchronization with external systems. The method of handling heterogeneous data as it was developed in the pilot project allows the creation of knowledge networks without a loss of information.

The analysis of hydro-geological conditions and hydraulic parameters of the aquifer is a reliable and indispensable basis. This includes the groundwater flow directions based on an up-to-date contour map and also takes climatic data, soil parameters and groundwater aging by isotope investigations into consideration,

In the pilot study several methods have been applied that transform environmental data into information that can be used effectively for managing resources. A key element of every management process is the knowledge of the total balance. For establishing a quantitative groundwater management, the total amount of groundwater resources, the total storage and the rate of annual renewal have to be known. Modern tools for establishing the elements of the balance have been applied. Based on these methods groundwater protection zones can be delineated.

The transformation of this scientific based knowledge to legal measures is essential for success. On this basis a strategy for general groundwater protection and measures to prevent groundwater pollution can be developed, the legal control of industrial plants and other hazardous substances, which may cause groundwater contamination can be set up. This includes creating the effective installation of drinking water protection areas by legalizing a catalogue of restrictions, prohibited activities and land use in these areas. The pilot project also showed that the patterns developed over a long period of time in Bavaria are a really good starting-point, but that an adjustment to the local conditions is necessary. This includes the creation of feasible protection areas and measures to be worked out with regard to existent land use already.

Within the pilot project it became obvious that the political goal of a sustainable usage of the Guarani Aquifer can be supported best by melting the knowledge of different disciplines, e.g.: The analysis of the isotopes and the hydro-geological conditions, the monitoring by an appropriate information system, the creation of legal conditions and rules - everything tailor-made for the specific local situation. The project was limited to the small region of Ribeirao Preto, but it has demonstrated that such tools can be implemented successfully and provide a basis for decision makers for the entire Guarani Aquifer - or for any other aquifer.

8. Contacts

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9. Acknowledgements

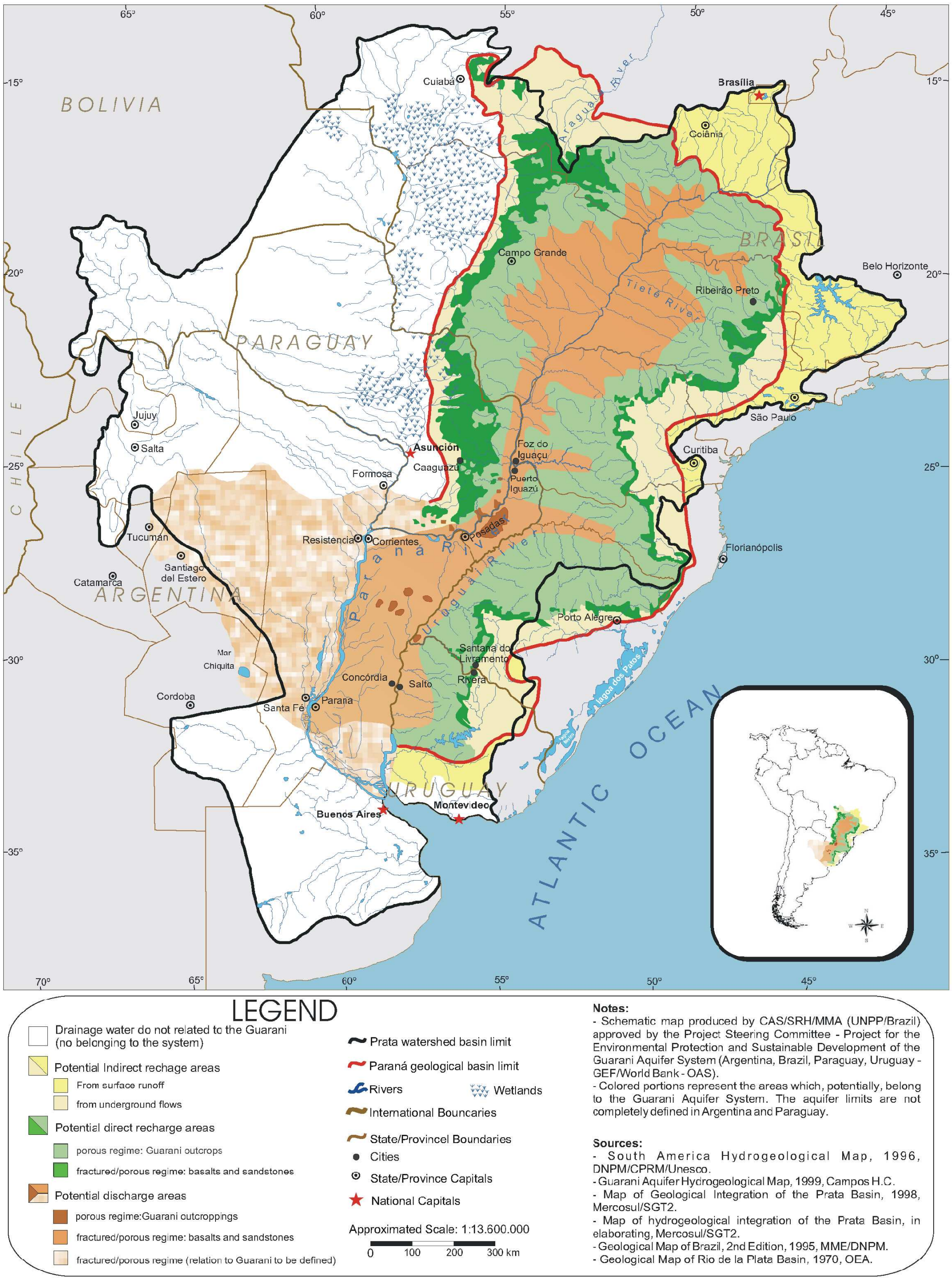
We want to thank the Prefeitura de Ribeirão Preto, the Departamento de Água e Esgotos de Ribeirão Preto (DAERP) and the Departamento de Águas e Energia Elétrica, SP. (DAEE) for providing data of the wells in the area of Ribeirão Preto.

Our Brazilian partners, members of the Instituto Geológico, Instituto Florestal and CETESB SP., organized by Dr. Mara Akie Iritani, Instituto Geológico, supported us by preparing the data, creating GIS-shape files, selecting and providing us with local technical literature, discussing our results in detail and giving critical and constructive suggestions to improve them. Prof. O. Sinelli, Universidade de São Paulo and co-operator of the Brazilian Team, presented outcrops of the Botucatu and the Serra Geral Formation and contributed hydro-geological details of the Guarani Aquifer in the region of Ribeirão Preto.

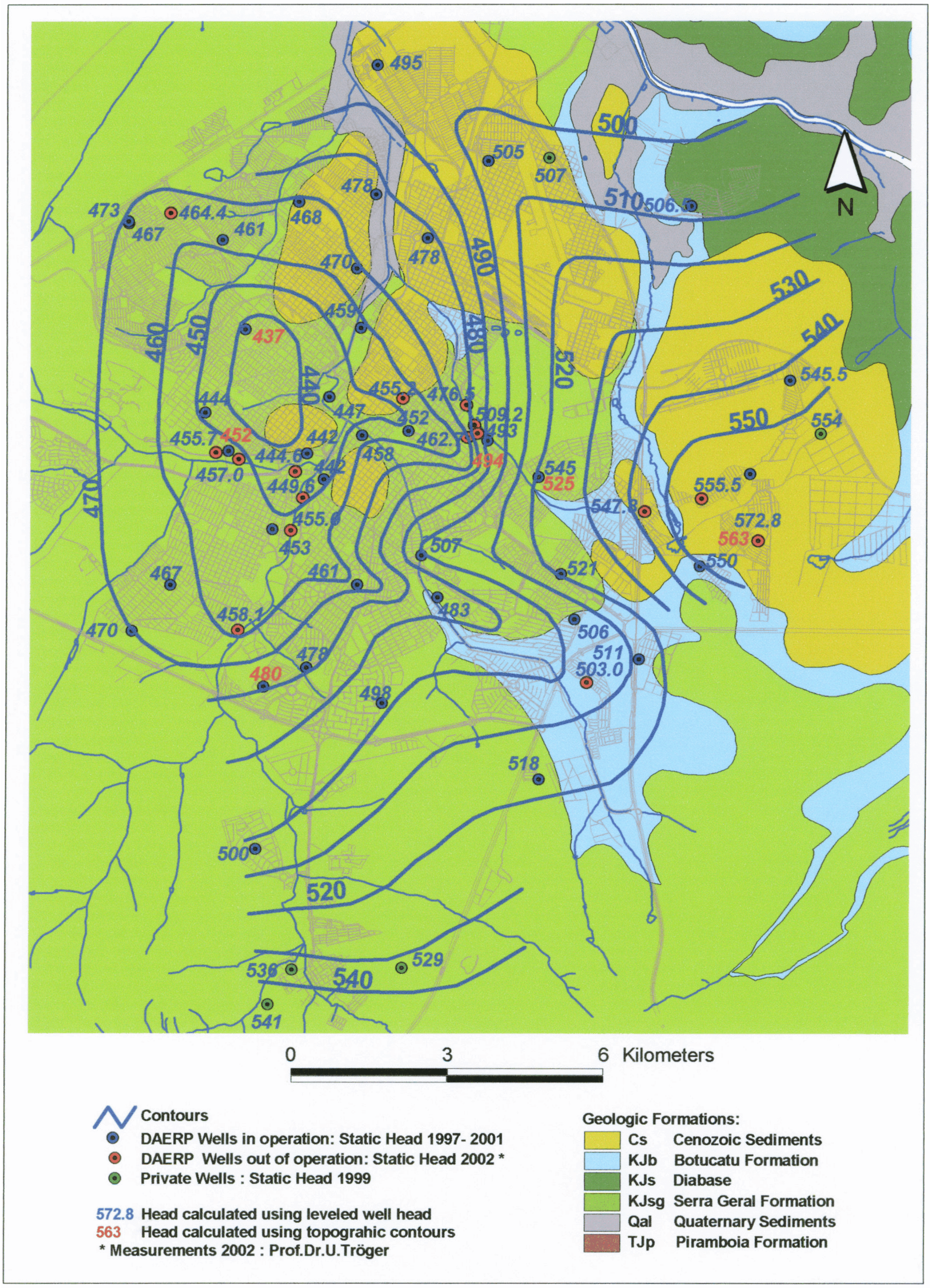
Our special thanks go to the "Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen", now "Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz" (Bavarian State Ministry for Regional Development and Environmental Affairs, now Ministry of the Environment, Public Health and Consumer Protection) and to TTW (Technology Transfer Water), Wasserwirtschaftsamt (State Office for Water Management), in Hof for the financial support as well as to the Secretaria do Meio Ambiente SP. for supporting our stays in São Paulo. Furthermore, we want to thank Prof. Dr. H. Frisch, former expert from the Bayerisches .Landesamt für Wasserwirtschaft (Bavarian Water Management Agency), München, who was the general coordinator for the Bavarian Ministry and Prof. Dr. U. Tröger, Coplan AG, Eggenfelden, for coordinating the work of the Bavarian Consultants and the cooperation with the Brazilian Team.

10. Annex

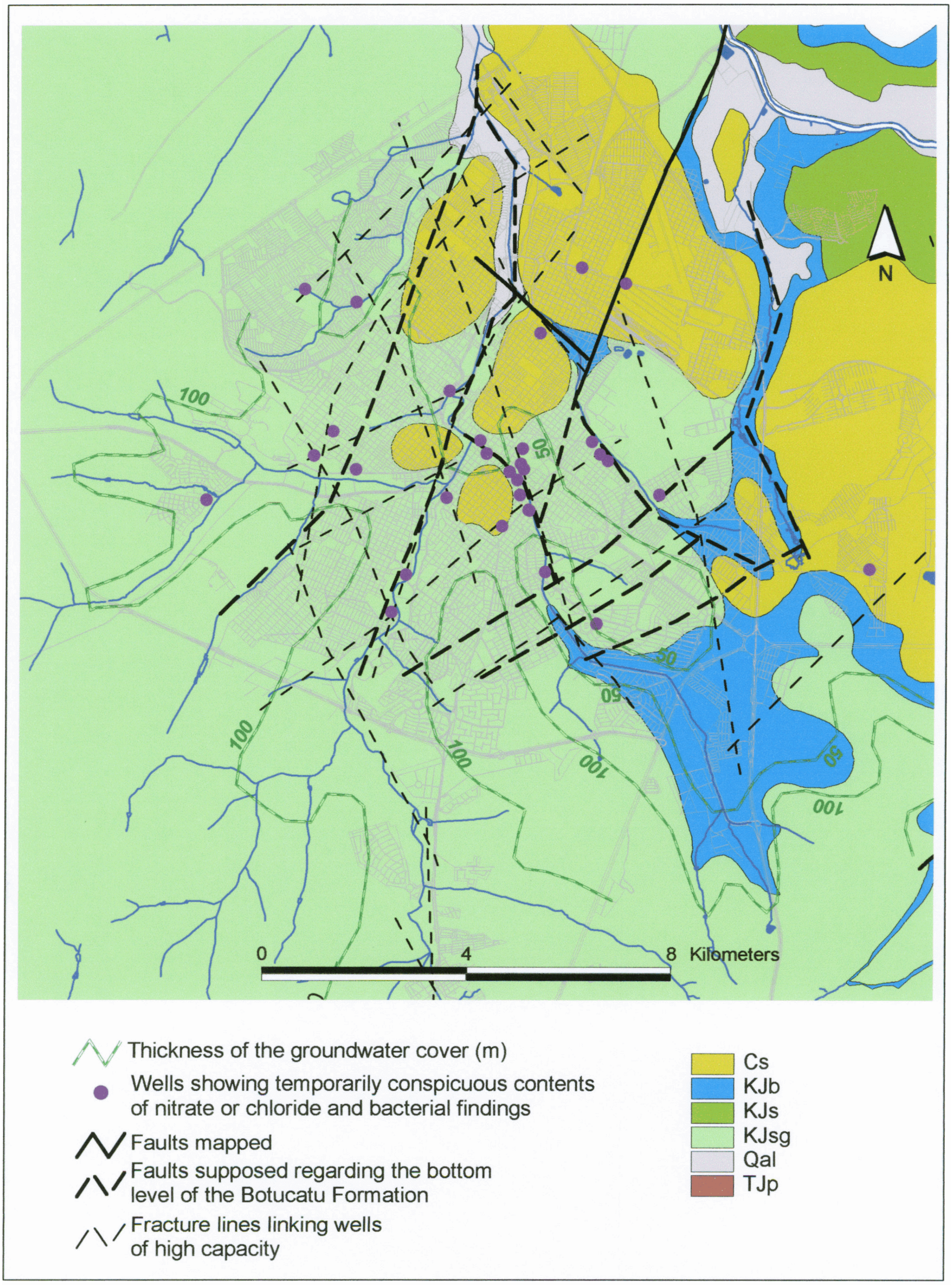
-1- Schematic Map of the Guarani Aquifer System



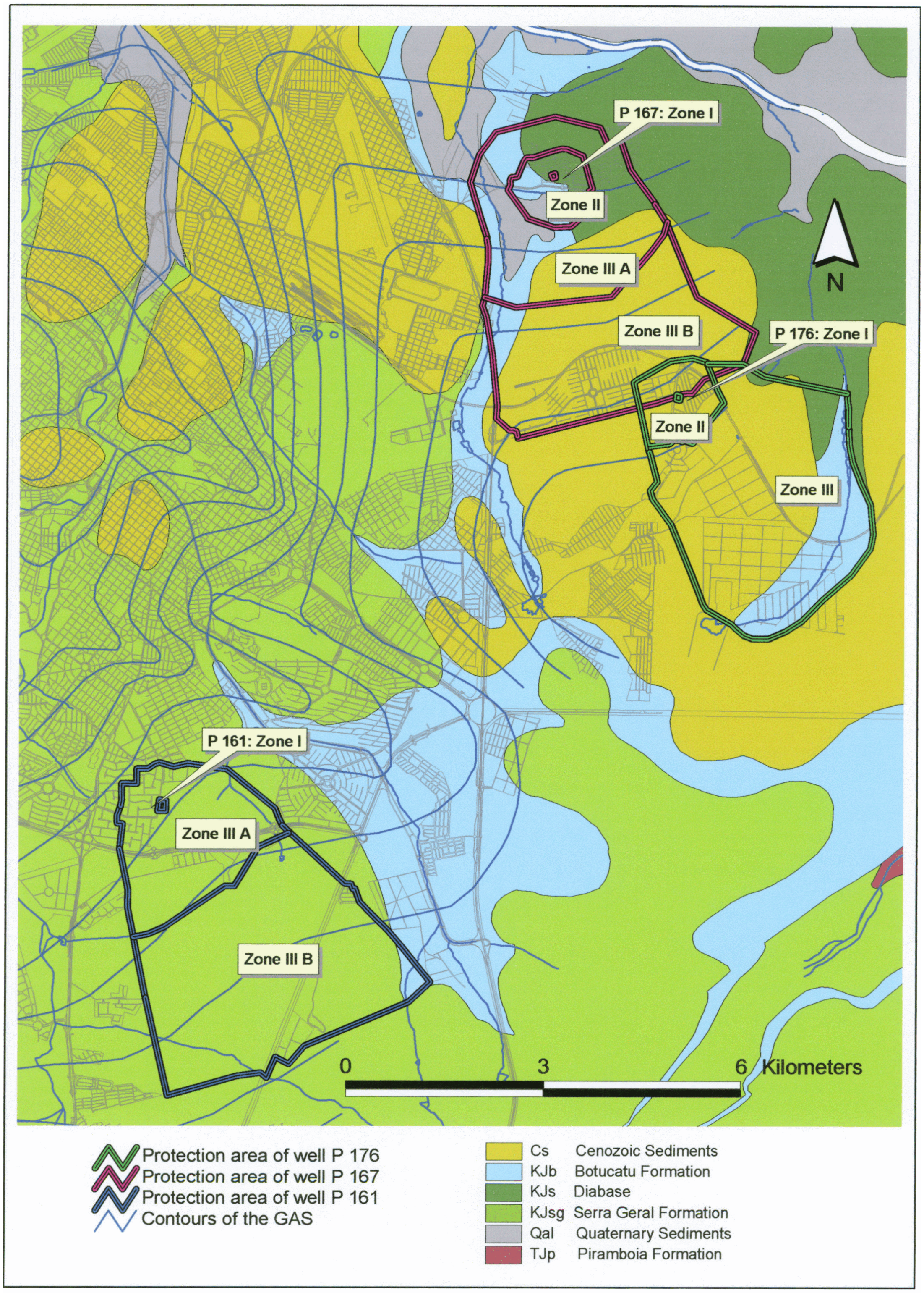
-2- Geology and Groundwater Contours



-3- Tectonic Structures and Groundwater Cover



-4- Drinking Water Protection Areas



-5- Catalogue of Restricted and Prohibited Activities

General Catalogue of Allowed, Restricted and Prohibited Activities and Land-use in Drinking Water Protection Areas (Extract)*

Preamble: In Zone I (Well protection area) all listed activities and uses are not allowed. Zone I must be fenced and must not be entered except by authorized persons.

		Zone II	Zone III A	Zone III B
1.	**Activities in Agricultural, Horticultural and Forestry Land-use**			
1.1	To use liquid and solid manure	not allowed	allowed like No.1.2	
1.2	Application of other organic or mineral nitrogenous fertilizers	allowed if fertilizing is executed at the right time and according to the demand; documentation must be done		
1.3	To store and to apply sludge of waste water treatment plants, sludge of domestic treatment and compost produced in central biologic treatment plants	not allowed		
....				
2.	**Other Land-use (as far as not regulated under No. 3 to 6)**			
2.1	Excavation or modification of the ground level even the groundwater is not touched, particularly fish ponds, gra-vel-, sand-, clay pits, quar-ries in hard rocks, open mining and peat cuts	allowed are regular agricultural and forestry activities		allowed if the protective effectiveness of groundwater covering layers is not remarkably hurted
2.2	Refilling of excavations	not allowed		
....				
3.	**Activities with Hazardous Substances**			
3.1	To install or to enlarge a network of pipes for the transportation of hazardous substances according to § 19 g of WHG (German Water Law)	not allowed		
3.2	To build or to enlarge plants according § 19 g of WHG for the production, treatment or application of hazardous substances	not allowed		allowed
....				
4.	**Waste Water Disposal and Waste Water Plants**			
4.1	To build or to enlarge waste water treatment plants	not allowed		allowed for clarification ponds: • if the permeability of the natural soil is lower than 10^{-8} m/s • or if the permeability of the natural soil is higher than 10^{-8} m/s and the bottom of the pond is artificially sealed
4.2	To build or to enlarge constructions for the relieve of rain water or mixed water systems	not allowed		allowed
....				
5.	**Trafic Ways, Places with a Special Determination of Use and Underground Mining**			
....				
5.2	To construct or to enlarge railroads	not allowed		allowed except shunting stations
5.3	To apply hazardous leachable and erodable materials for road, railroad and hydraulic construction, for example slag, tar, impregnation material and others	not allowed		
....				
6.	**Buildings of Civil Engineering in General**			
6.1	To construct or to enlarge buildings of civil engineering	not allowed	• allowed if the waste water is discharged in an impervious main sewage system; No. 4.7 must be respected • allowed if the foundation level is more than 2 m above the highest groundwater level	• allowed if the waste water is discharged in an impervious main sewage system; No. 4.7 must be respected • allowed if the foundation level lies above the highest groundwater level
....				

** according to the manual of the Bavarian Water Management Agency (Bayer. Landesamt für Wasserwirtschaft, Munich)*

-6- The Administrative Way of the Decree of a Drinking Water Protection Area in Bavaria

Decision of a water supplier to apply for a drinking water protection area

↓

Commission of a hydrogeological consultant for the elaboration of the application documents

↓

Elaboration of the application documents by the hydrogeological consultant

↓

Submission of the application documents to the District Office
(local Administrative Authority by the water supplier)

↓

Comment on the application documents by the local State Office for water Management

↓

Hearing of the public planning institutions and of the concerned land owners

↓

Comment on the objections of concerned people by the Local State Office
For Water Management (Official Expert)

↓

Discussion with the concerned people under the chairman-ship of the District Office

↓

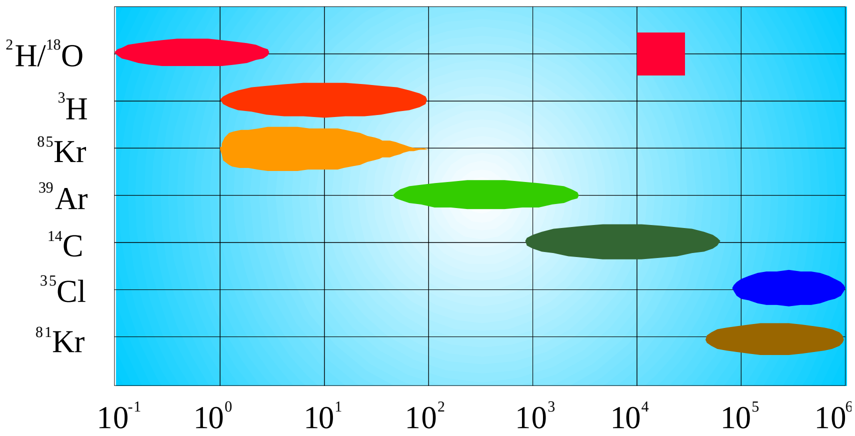
Enactment of the decree by the Office District

↓

Possible legal appeal against the decree in Bavaria: Highest Administrative Court
in Bavaria

-7- Isotope Applications in Hydrology

Isotope methods give direct information on the water cycle components: the age, the origin and the distribution in time and in space can be characterized. A series of isotope tools are available for hydrological and hydro-geological applications: *groundwater age dating* and *origin assignment of groundwater components or pollutants*. Isotope methods give insight into average groundwater ages on a scale from days to hundreds of thousands of years.



Isotopes and their application for groundwater ages of different time scale (years)

Age dating methods are chosen depending on the time scale of the average turnover time. For relatively young groundwater, the tritium content, Krypton-85 and Argon-39 provide information. Carbon-14 enables the distinction of groundwater ages from 1500 years up to about 40.000 years. Carbon-14 is an important tool for deep groundwater systems with low flow velocities in the range of meters per year. Chloride-35 and Krypton-81 apply to very old groundwater samples.

Groundwater wells often receive contributions from different groundwater components, such as a component from the regional flow systems and another from local riverbed infiltration. Also different geologic formations can produce groundwater with different “fingerprints”. Differences of altitude and of recharge mechanisms, sometimes of land-use can be traced back with stable isotopes. Stable isotopes are also being used for studying groundwater vulnerability and the origin of borehole deterioration, the origin and type of pollution.

-8- The Soil Water Balance Model Regis

The hydrological processes have been simulated with a recent version of the water balance model REGIS. This software calculates the soil water balance. For the chosen system all inflows are integrated and added, net change in storage is accounted for and all the water losses are subtracted in order to obtain groundwater recharge as the resulting term.

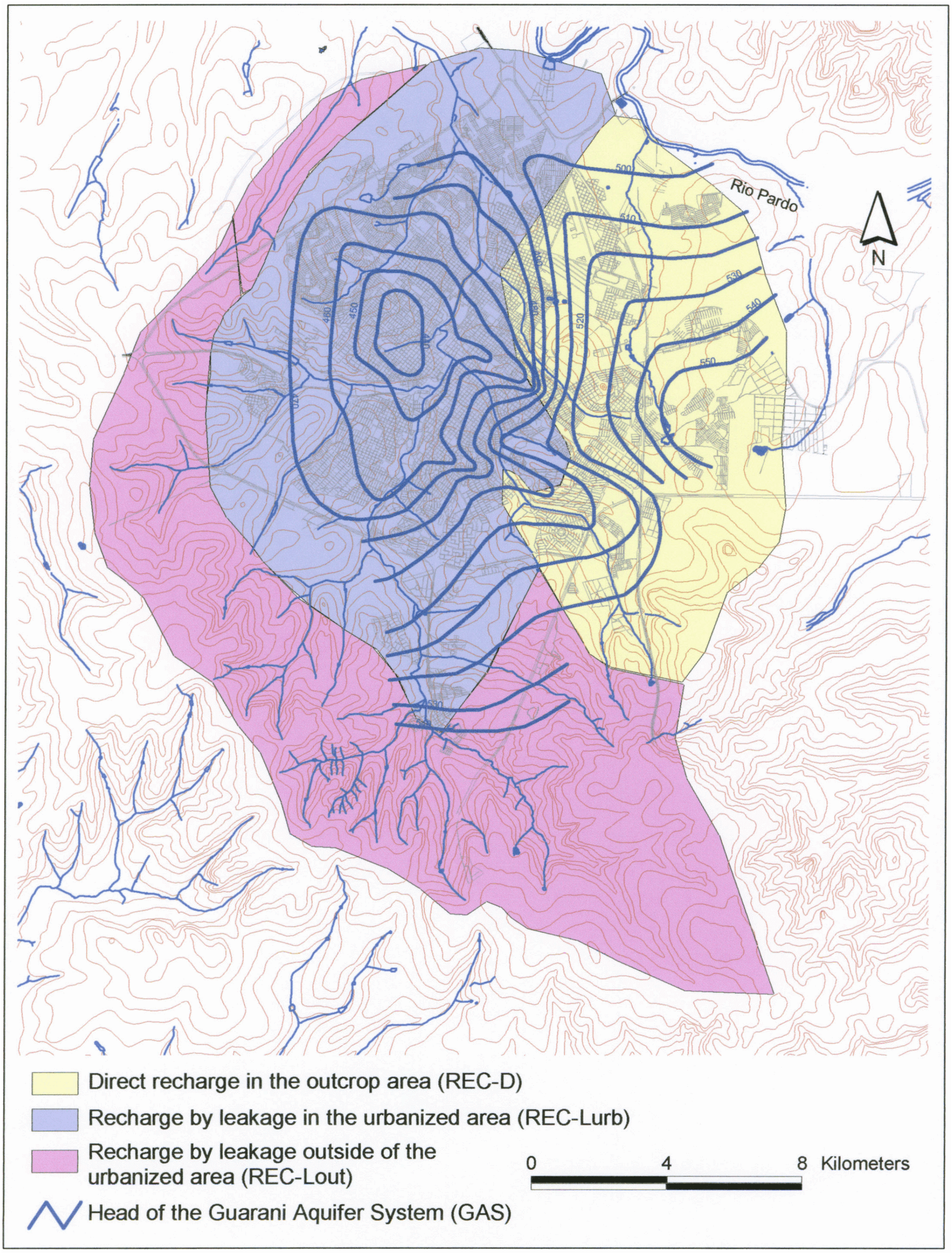
The model calculates interception losses, runoff generation, infiltration, soil moisture storage, interflow, evaporation and groundwater recharge on a daily basis. It can process data from single observation points and from maps that are entered as raster files. REGIS requires time series of meteorological data and maps of parameters of land-use, of the soil and subsoil. As meteorological parameters, daily rainfall, temperature (°C) and relative humidity (%) are needed. REGIS needs a raster of the total terrain elevation above sea level for an altitude correction of temperature and rainfall. At each raster element, the soil is characterized by the slope, infiltration rate in mm/event, effective field capacity (mm/soil column) and hydraulic conductivity of the soil layer (m/s). In addition, the bedrock permeability (m/s) is specified in different classes.

The model also provides the possibility to calculate river discharge. River discharge is modeled as a combination of direct and fast surface runoff and of baseflow. Baseflow is linked to the storage in the aquifer by an exponential law. The recession parameter is estimated from discharge records or from regional data. Leakage through the aquifer base can be accounted for using Darcy’s law and porosity. Model calibration is made by comparing soil moisture data or the sum of accumulated direct runoff and of baseflow over the whole study area to observed discharge time series, or by comparing groundwater level time series.

KÜLLS C. & UDLUFT P. (2000): Mapping the availability and dynamics of groundwater recharge. Part II: Case studies. 3rd Congress on Regional Geological Cartography and Information Systems, Proceedings, München 2000: pp. 163-168

UDLUFT P. & KÜLLS C. (2000): Mapping the availability and dynamics of groundwater recharge. Part I: Modelling techniques. 3rd Congress on Regional Geological Cartography and Information Systems, Proceedings, München 2000: pp. 337-340

-9- Catchment Area and Recharge Zones



-10- Numerical Optimization

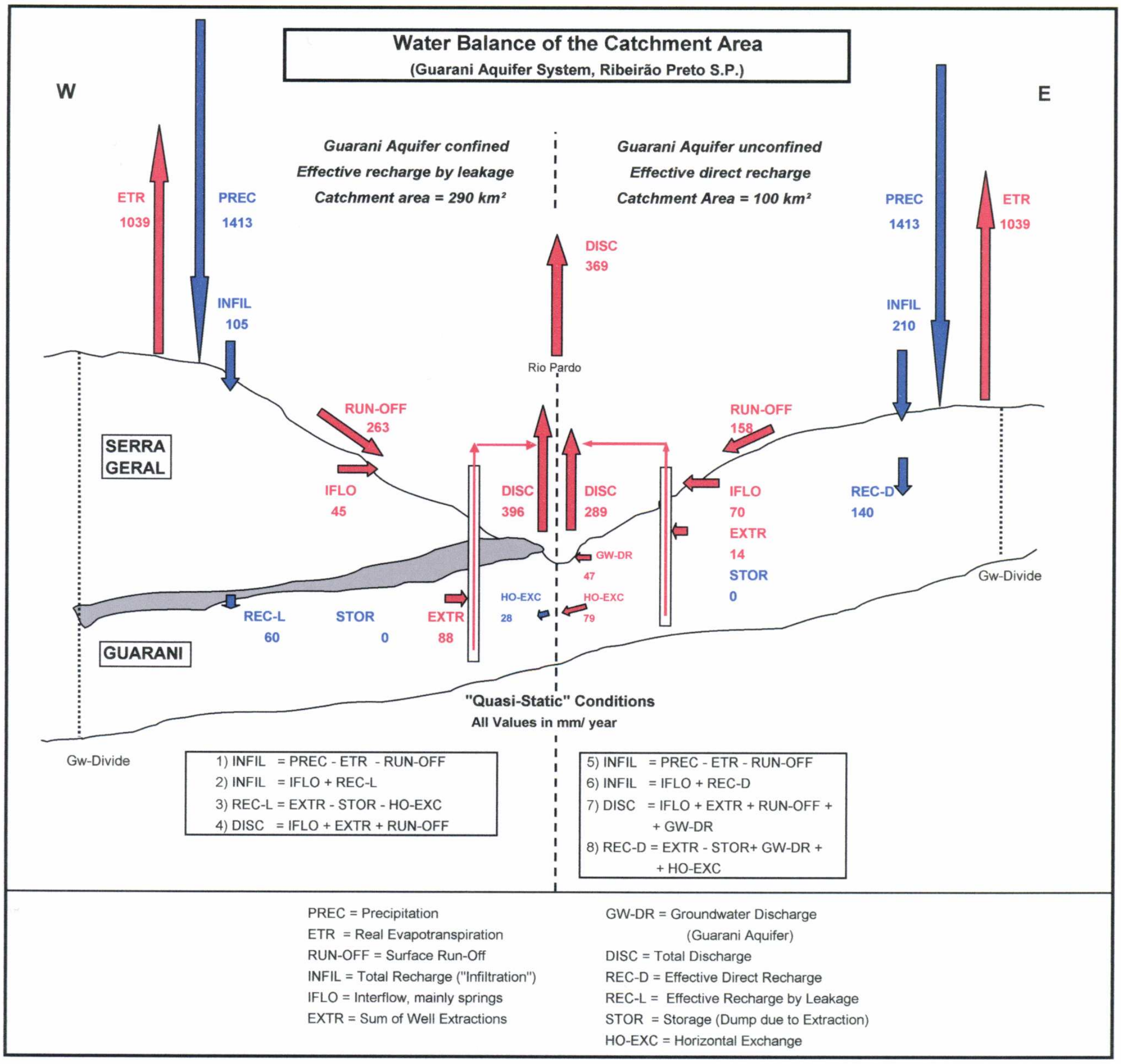
Model Parameters										Quality of the Results	
Model Run	Hydraulic Conductivity	Anisotropy NE/ NW	Effective Porosity*	Storage Coefficient	Recharge Rates			Ratio	Well Extractr. Time Period 6	Plausibility of the computed contours	Plausibility of the ratio
					Outcrop Area	Urban.Area	Not urb.Area	REC-L_{out}/			
	K	K_{NE}/ K_{NW}	n_e	S	REC-D	REC-L_{urb}	Comp.REC-L_{out}	REC-L_{urb}	Q		REC- L_{out} / L_{urb}
No.	m/s	-	-	-	m/s	m/s	m/s	-	l/s	-	-
2000	1,00E-05	1,33	0,05	5,00E-04	5,00E-09	1,50E-09	1,80E-09	1,2	766	o	+
2010	1,00E-05	1,33	0,10	5,00E-04	5,00E-09	1,50E-09	1,70E-09	1,1	766	-	+
2100	1,50E-05	1,33	0,05	5,00E-04	5,00E-09	1,50E-09	2,00E-09	1,3	766	o	+
2110	1,50E-05	1,33	0,05	5,00E-04	5,50E-09	1,50E-09	1,90E-09	1,3	766	-	+
2200	1,50E-05	1,33	0,05	5,00E-04	5,00E-09	2,50E-09	1,30E-09	0,5	766	-	-
2210	1,50E-05	1,33	0,05	5,00E-04	5,00E-09	1,00E-09	2,40E-09	2,4	766	-	-
232210	1,50E-05	1,33	0,05	5,00E-04	5,00E-09	1,00E-09	2,30E-09	2,3	793	-	-
2220	1,50E-05	1,33	0,05	5,00E-04	5,00E-09	1,35E-09	2,10E-09	1,6	766	-	-
2230	1,50E-05	1,33	0,05	5,00E-04	5,50E-09	2,00E-09	1,50E-09	0,8	766	-	-
2300	**1,25E-05**	**1,33**	**0,05**	**5,00E-04**	**5,00E-09**	**1,50E-09**	**1,90E-09**	**1,3**	**766**	**+**	**+**
232300	**1,25E-05**	**1,33**	**0,05**	**5,00E-04**	**5,00E-09**	**1,50E-09**	**1,80E-09**	**1,2**	**793**	**+**	**+**
2303	1,25E-05	1,00	0,05	5,00E-04	5,00E-09	1,50E-09	1,90E-09	1,3	766	o	+
2304	1,25E-05	0,50	0,05	5,00E-04	5,00E-09	1,50E-09	1,90E-09	1,3	766	-	+
2305	**1,25E-05**	**1,33**	**0,10**	**5,00E-04**	**5,00E-09**	**1,50E-09**	**1,80E-09**	**1,2**	**766**	**+**	**+**
2306	**1,25E-05**	**2,00**	**0,05**	**5,00E-04**	**5,00E-09**	**1,50E-09**	**1,90E-09**	**1,3**	**766**	**+**	**+**
2307	1,25E-05	1,33	0,025	5,00E-04	5,00E-09	1,50E-09	2,00E-09	1,3	766	o	+
2308	**1,25E-05**	**1,33**	**0,05**	**1,00E-04**	**5,00E-09**	**1,50E-09**	**1,90E-09**	**1,3**	**766**	**+**	**+**
2310	1,25E-05	1,33	0,05	5,00E-04	5,00E-09	2,00E-09	1,60E-09	0,8	766	+	-
2320	1,25E-05	1,33	0,05	5,00E-04	5,00E-09	1,00E-09	2,30E-09	2,3	766	O	-
2330	1,25E-05	1,33	0,05	5,00E-04	5,00E-09	2,25E-09	1,40E-09	0,6	766	O	-
2340	**1,25E-05**	**1,33**	**0,05**	**5,00E-04**	**5,00E-09**	**1,35E-09**	**2,00E-09**	**1,5**	**766**	**+**	**+**
232340	**1,25E-05**	**1,33**	**0,05**	**5,00E-04**	**5,00E-09**	**1,35E-09**	**1,90E-09**	**1,4**	**793**	**+**	**+**
2350	1,25E-05	1,33	0,05	5,00E-04	5,00E-09	1,75E-09	1,70E-09	1,0	766	+	-
2360	1,25E-05	1,33	0,05	5,00E-04	4,50E-09	1,50E-09	2,00E-09	1,3	766	o	+
2401	1,75E-05	1,33	0,05	5,00E-04	5,50E-09	1,75E-09	1,80E-09	1,0	766	o	-
2402	1,75E-05	1,33	0,05	5,00E-04	6,00E-09	1,50E-09	1,90E-09	1,3	766	-	+
2403	1,75E-05	1,33	0,05	5,00E-04	5,50E-09	1,50E-09	2,00E-09	1,3	766	-	+
2601	2,00E-05	1,33	0,05	5,00E-04	7,00E-09	1,50E-09	4,10E-09	2,7	1266	-	-
2602	2,00E-05	1,33	0,05	5,00E-04	7,00E-09	2,00E-09	3,70E-09	1,9	1266	-	-
2603	2,00E-05	1,33	0,05	5,00E-04	7,00E-09	2,25E-09	3,50E-09	1,6	1266	-	-
2604	2,00E-05	1,33	0,05	5,00E-04	7,00E-09	2,50E-09	3,30E-09	1,3	1266	-	-
2701	2,00E-05	1,33	0,05	5,00E-04	6,00E-09	2,00E-09	2,30E-09	1,2	919	-	-
2702	2,00E-05	1,33	0,05	5,00E-04	7,00E-09	2,00E-09	2,20E-09	1,1	919	-	-
2801	2,00E-05	1,33	0,05	5,00E-04	5,00E-09	1,50E-09	2,50E-09	1,7	843	-	-

* Specific Yield

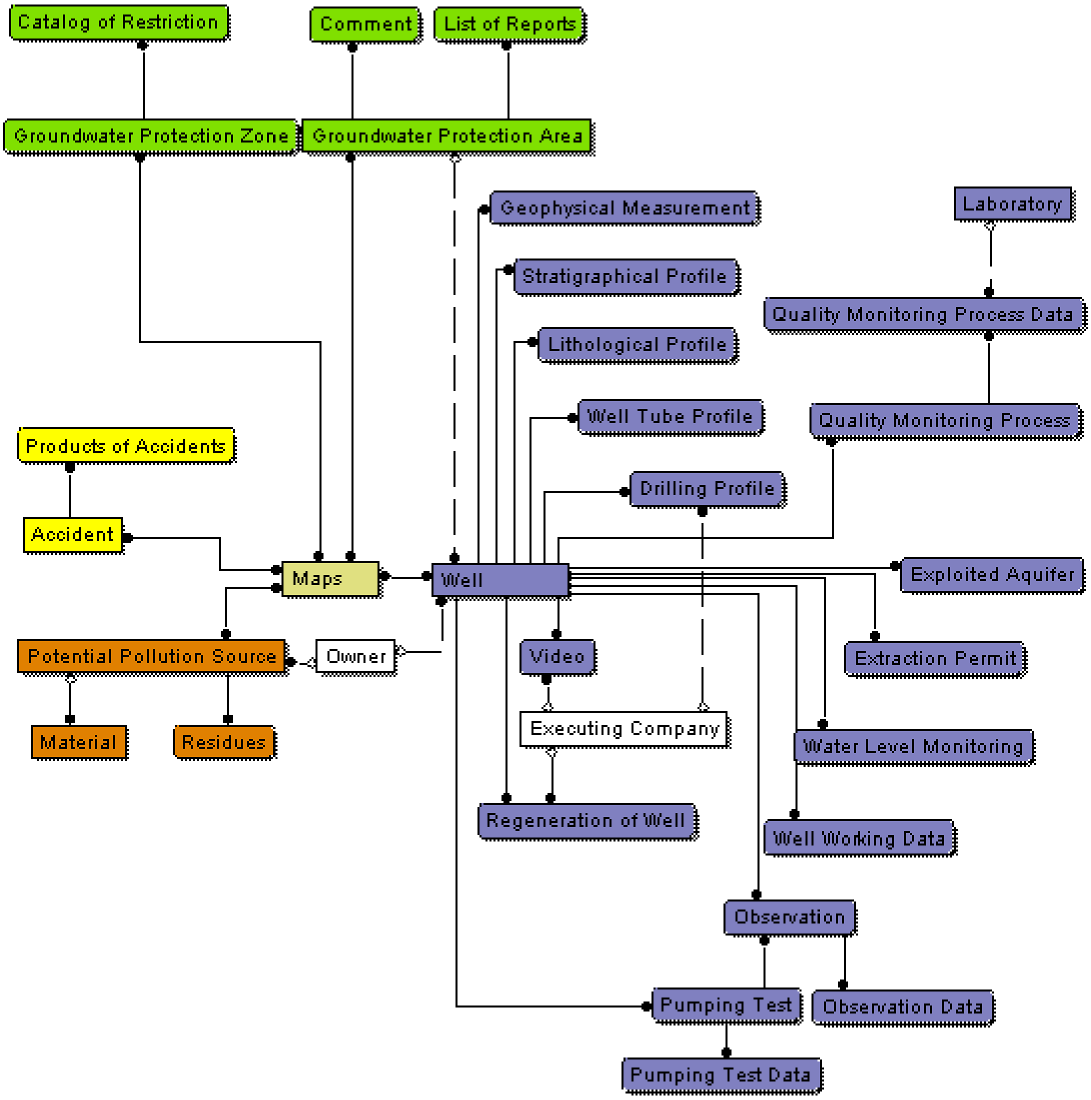
Model Time Periods

Model Period	Real Time Period	Years
1	1909 -1919	10
2	1919 - 1948	30
3	1949 - 1964	15
4	1965 - 1982	17
5	1983 - 1994	12
6	1995 -2000	6

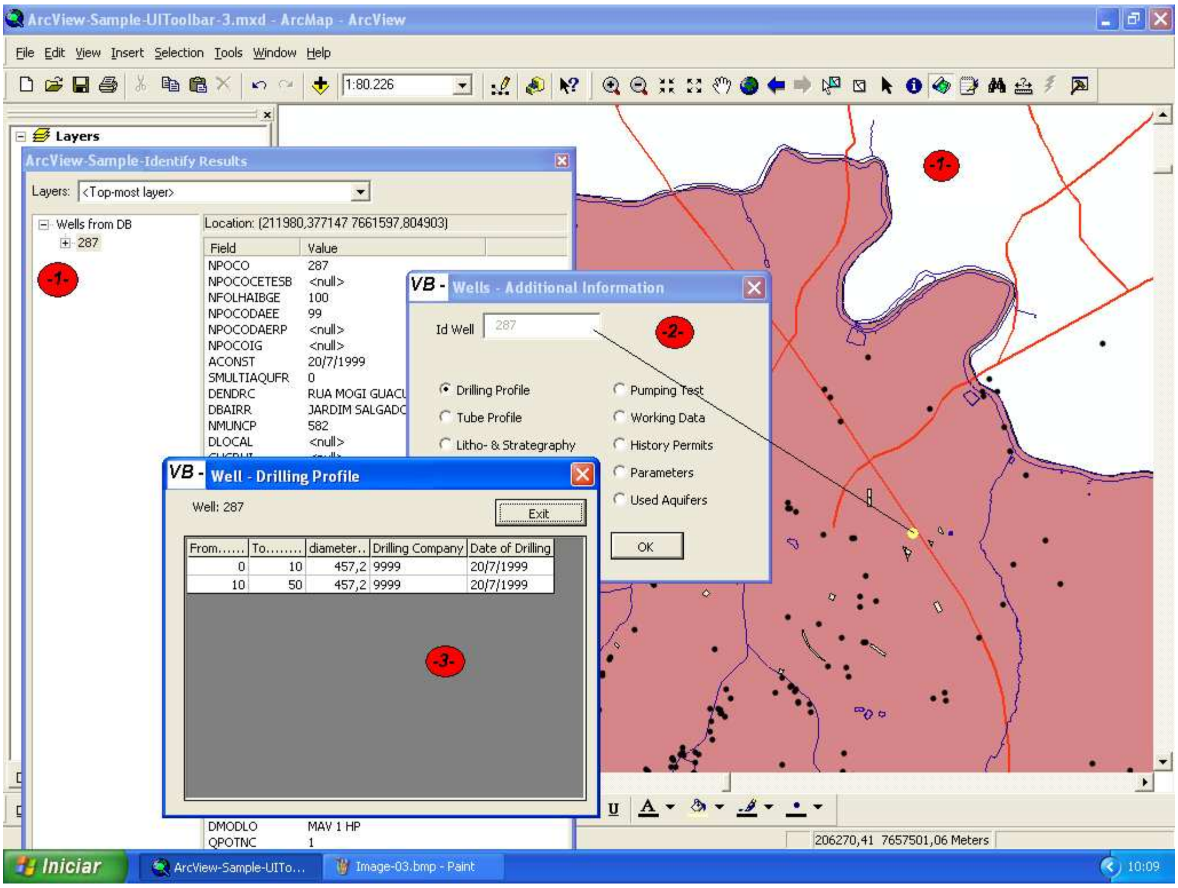
-11- Catchment Water Balance



-12- Entity Relationship Model (Simplified Version)



-13- Application for Analysis – Samples



The figure shows three steps of work:

-1- A selection of a well in ArcView and the standard information derived from the table "Well"

-2- The invocation of a navigation tool ("Additional Information") to related tables to the entity "Well"; this navigation tool is started by a customized toolbar icon (the last one within the visible toolbar), invoking a Visual Basic application. This step represents the bridge from ArcView to the VB-application that allows the drill-down to all related information.

-3- The "Drilling Profile" of the selected well as one of the possible related tables, an example of a related table to the selected feature.