Internationale Zusammenarbeit in Umwelt und Entwicklung; Förderung einer Machbarkeitsstudie für das Projekt TTW der Bayerischen Wasserwirtschaftsverwaltung am Wasserwirtschaftsamt Hof

"Information System of Groundwater Resources Environmental Management in the Outcrop of the Guarani Aquifer in the São Paulo State, Brazil"

Final Report for the Project Part "Groundwater Recharge"

Groundwater Recharge of the Guarani Aquifer in the Pilot Area of Ribeirão Preto (Guarani Aquifer Pilot Project)"

Prepared by: Dr. C. Külls

Content

Acknowledgement

The support from the Bavarian State through the Project Technology Transfer Water at the 'Wasserwirtschaftsamt Hof' and the support from our Brazilian Partner, the Instituto Geológico São Paulo, is greatfully acknowledged.

We would like to thank for the very good cooperation with the Brazilian team at the Instituto Geológico, especially Mara Iritani for their great support and coordination of the activities. The technical input from the whole team for the parameter estimation of the water balance model was crucial. We would also like for the support and the personal efforts during the isotope sampling campaign.

We are greatful for the good technical cooperation and fruitful discussions with the Bavarian companies, namely IT & More and Prof. Schuler. Finally, we wish to thank for the project steering and technical coordination done by Prof. Frisch and Prof. Tröger during the whole project.

Abbreviations

CFC Chlorofluorocarbons
^{85}Kr Krypton 85, radioactive isotope of the gas Krypton
SF_6 Sulfurhexafluoride

Executive Summary

The major objective of this work is to study groundwater recharge as a quantitative basis for groundwater management in the pilot study area Ribeirão Preto. First, an extensive literature review was carried out listing the available studies in Brazil. These studies were analysed and summarized for the first meeting in S. Paulo. The overview indicated that mainly aquifer studies (Darcy), soil water balance methods and some base flow studies were used to determine recharge. There is a lack of conceptual model buidling and of detailed isotope studies. It was concluded that the soil water balance approach should be consolidated based on the existing work. In a second step the data availability was discussed at CETSB and at the Geological Insitute for point data and for spatial data sets. Meteorological daily data for temperature, relative humidity, rainfall and even for some special parameters (sunshine hours, windrun) are available. The quality of discharge data in Ribeirão Preto is considered to be poor. At the Instituto Florestal, the software equipment (ArcView) and the spatial data for distributed soil water balance models exist and have been made available for the project.

Among the many existing soil water atmosphere transfer (SWAT) models, two were chosen for the project. **AVSWAT-2000** is an ArcView extension and a graphical user interface for the SWAT (Soil and Water Assessment Tool) model. SWAT is a river basin, or watershed, scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient, uses readily available inputs, and enables users to study long-term impacts. The second model is **REGIS** (**Re**gional **G**roundwater recharge **I**nformation **S**ystem) developed by the author. This model is used for training purposes and point estimation of recharge. This model has been applied in Europe and in Brazil within the project WAVES (Water availability and vulnerability of Ecosystems and Society) – it represents the same physical processes as AVSWAT 2000. The model calculates, interception losses, runoff generation, soil moisture storage, inter-flow and groundwater recharge. It requires meteorological data and soil/aquifer parameters.

For the model Regis all the time series data (meteorology) and spatial data sets have been prepared. The preparation of the time series data included rainfall, relative humidity, and temperature. The data set extends from the 1st of January 1996 until the 31st of December 2001.

Using the model Regis 1.0, the potential evaporation was calculated for the whole time period based on the approach of Priestley-Taylor, which is a modified Penman-equation. The rainfall and potential evaporation were used to calculate a water balance for every specified cell of the study area.

For this step, input files of spatial data sets for the parametes (topography, land-use / vegetation, effective field capacity, hydraulic conductivity and sub-soil conductivity) have been prepared.

The preparation of these input files was done jointly with experts from CETESP and Instituto Geologico and Instituto Florestal during the second working meeting in S. Paulo. Based on the parameter maps and the input time series of meteorological parameters, different runs for the determination of recharge were made. The runs have been carried out for typical land-use / soil complexes and for the study area as a whole.

The total actual evaporation figures corresponded well with existing data (about 1050 mm/y). The different runs yielded direct recharge rates of 130 to 150 mm/y for soils of average thickness. The recharge timing could already be derived with first events starting in December and the major peak following in February to March.

A major part of the rainfall of 1413 mm/y evaporates and is used for transpiration. Due to the thick soils, quite impermeable texture and good storage properties, the recharge rates are quite low on average. Direct runoff amounts to 236 mm/y. The total runoff also includes indirect runoff components such as interflow that are generated within the soil profile due to low subsoil permeability. The total runoff amounts to 368 mm/y. The storage change is due to differences in soil moisture state between the beginning of the model run and the final state.

The average recharge rate is 132 mm/y. Locally recharge rates reach values of 250 mm/y. Higher recharge rates are observed were the soil texture is sandy and were land-use with shallow root depth prevails. In the area confined by the Serra Geral Formation recharge is still significant and reaches 50 to 100 mm/y. The percentage of interflow in this area is very difficult to estimate since the physical properties of the fractured aquifers are not well known. The results show that in spite of high rainfall amounts recharge is comparatively low due to the fact that rain falls during the warm summer and evaporation rates are high. The soil has good storage properties, reducing the amount of fast percolation and providing water storage for evaporation. Recharge takes place mainly between December and February. This is confirmed by the fact that the isotopic signature of the groundwater corresponds to the isotopic signature of rainfall of these months. The model is not calibrated. Since the water balance model is based on physical parameters the results are valid within the accuracy of the simplification of physical processes and parameters. However, these results require a validation with independent methods. The isotope investigations should be extended to ^{14}C studies along flow-paths in the Botocatu aquifer. The study of young groundwater should include Tritium / Helium analyses or other trace gases such as Sulfurhexafluoride or Chlorofluorocarbons (CFCs.

1 Study on the recharge of the Guarani Aquifer – Framework and objectives

The rate of groundwater recharge in the pilot area Riberão Preto is determined in cooperation between the project partners and institutions in Brazil and Bavarian consultants. Part of these investigations is the development of a conceptual model based on isotopic studies.

1.1 General objectives

The general objectives of the project were to collect the relevant data concerning the groundwater resources and to organize them in a central database, to develop and propose drinking water protection areas in unconfined and confined parts of the aquifer. Based on the available data in the study area the groundwater recharge should be estimated as a basis for the management of groundwater resources in the future.

1.2 Objectives of the study by Hydroisotop GmbH

The major objective of this work is to study groundwater recharge as a quantitative basis for groundwater management in the pilot study area. Based on the analysis of available literature, taking into account the state of the art a method should be proposed that

- is adequate for the natural environmental conditions in the study area
- incorporates the existing data and studies
- provides groundwater recharge information in an economic and adequately precise way
- gives a figure for the amount that can be used in a sustainable way

Within the study first the existing data and methods were evaluated, only then otherwise suitable methods were considered. Finally, an adequate method was selected, proposed, adjusted and applied.

Isotope investigations have been part of this study. Isotope methods have been applied for several reasons:

1. In previous studies a lack of direct information helping to establish conceptual models on flow patterns and hydrogeological background information has been noted. Isotope studies can help to get such information.
2. Until now there are only very few data on groundwater age structure. The data are limited to carbon-14 analyses that have methodological limitations due to isotope exchange reactions, especially in the presence of carbonate sediments.
3. An important aspect of the project is to demonstrate the expertise of Bavarian laboratories in the field of modern hydrogeology and information technology. Isotope methods form part of the key qualifications for a future World Bank Project.
4. Isotope data can help to verify groundwater recharge estimations and can give additional information for the establishment of groundwater models.

Due to budget constraints the isotope investigations have been limited to application of stable isotopes of oxygen and deuterium and of tritium. The results have been used to verify the conceptual model and to constrain groundwater recharge rate estimations.

1.3 Program of work

A literature review has been prepared by Prof. Dr. Tröger and a working group in S. Paulo. The literature was analysed and used for this study. This preparatory phase covered November 2002.

A first draft on the methodology and available references was prepared for the beginning of December 2002, presented and discussed in a joint meeting with the Brazilian partners. As a result of the meeting a method for the analysis of groundwater recharge was chosen. In the first month of the year 2003 data were collected for the water balance approach and a first recharge estimation was derived for the pilot study area. These results have been presented, discussed and finalized in a second meeting in April 2003 with the Brazilian counter-parts. An interim report was prepared in April 2003 containing the first results of the water balance modelling.

Between the second meeting (April 2003) and the final meeting the recharge estimation has been extended to a distributed modelling approach. The results of the distributed water balance modelling and the recommendations for future monitoring strategies are discussed in this report.

2 Quantitative groundwater recharge estimation

The process of groundwater recharge can be quantified by

- ***Forward*** approaches estimating the infiltration with water balance approaches of the soil or other process-oriented infiltration models
- ***Backward*** approaches estimating recharge from the *resulting* change of storage in the aquifer, water level responses or space- and time-integrating isotope and hydro-chemical characteristics of the groundwater. Also fitting of groundwater models is based on the resulting groundwater levels.

The first step should always be an analysis of the hydrological and geological environment. A conceptual model (Hydrogeological Model) of how recharge takes place and of how groundwater flows should be established *before* methods are chosen and before data are collected. The relative importance of direct and indirect recharge mechanisms is a major criterion for the choice of forward or backward estimation methods. If direct recharge is the dominant recharge mechanism, the forward numerical or experimental analysis of vertical moisture flow is a suitable approach. Water balance methods and solute profile methods can be applied.

If indirect recharge mechanisms are dominant, runoff generation and distribution become important, controlling riverbed infiltration. Preferential recharge areas or lineaments (river sections) need to be identified. In this context isotope and hydrochemical indicators as well as inverse methods become helpful tools and have been used for the delineation of favourable recharge areas in complex terrain. If the geological conditions are favourable, recharge rates can also be derived from water level fluctuations or from basin outflow (base flow).

2.1 Forward methods

A classic approach of direct forward recharge estimation is based on the climatic or soil water balance. Any water balance approach requires a definition of a hydrological system for which the individual components of the hydrological cycle are balanced. This may be a vertical soil column, a river reach with defined inlet, and/or a river basin. 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.

2.1.1 Distributed and lumped climatic and soil water balance methods

For a vertical soil column, the discrete form of a water balance formula writes as:

$$R(t) = P(t) - ETP(t) - Q(t) \pm \Delta S$$

with *R(t)* as recharge, *P(t)* precipitation, *ETP(t)* evapotranspiration, *Q(t)* runoff and ΔS change in water storage. A model of hydrological processes between the atmosphere and the soil zone can be used as a basis for computing daily soil water balances and percolation rates. Such models, called SVAT models (Soil-Vegetation-Atmosphere-Transfer) are now also available as distributed models with GIS interface (ARNOLD ET AL., 1998, ARNOLD & ALLEN, 1992).

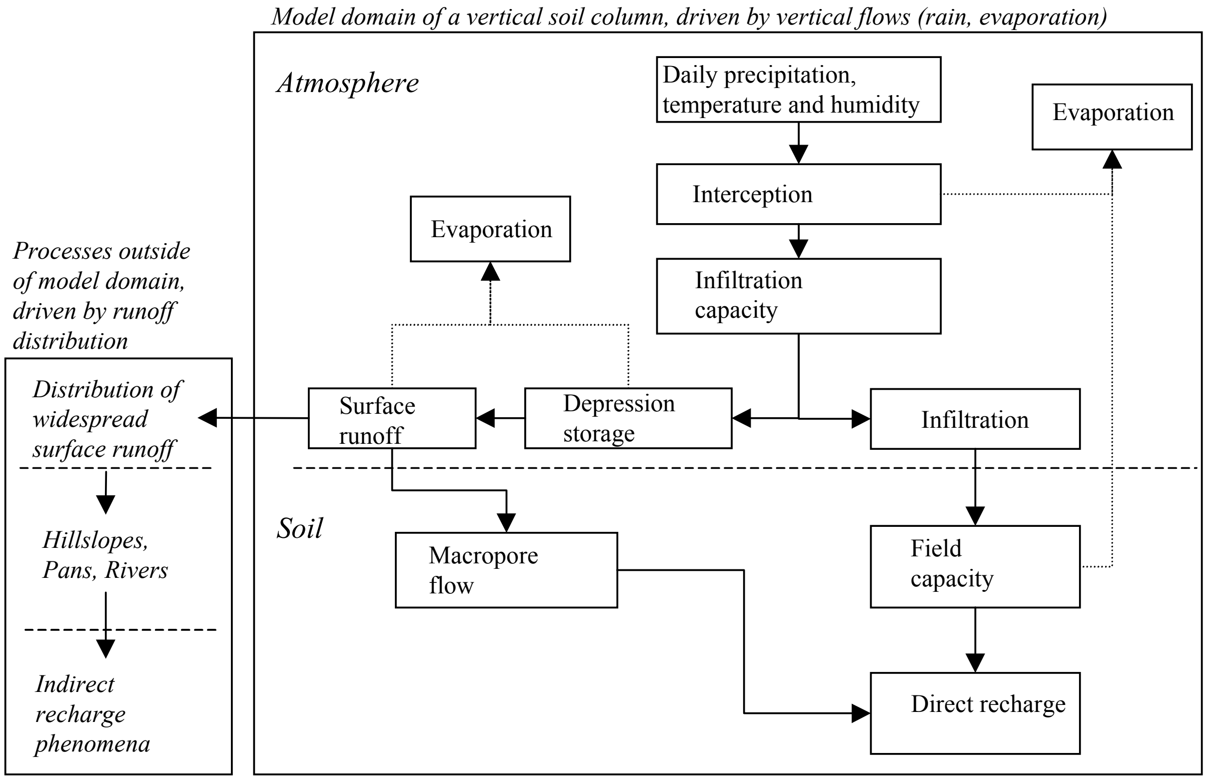


Figure 1 Flow chart representing the water balance model programmed with daily input parameters (rainfall and evaporation in mm), constant parameters (interception, infiltration capacity, field capacity, macropore flow factor), and computed daily data (infiltration, surface runoff, direct recharge).

SVAT models can be used for the computation of daily recharge. Daily rainfall, temperature and relative humidity or pan evaporation are needed as input parameters. Actual transpiration is deduced from actual soil moisture storage on a daily basis. Recharge is produced when the soil moisture reaches or exceeds field capacity. The computed runoff inducing indirect recharge by transmission losses can be accounted for.

2.1.2 Flow estimation based on Darcy's law

The flow estimation based on Darcy requires rather precise hydrogeological data on the gradient and on the hydraulic conductivity. Hydraulic conductivity being difficult to estimate even in terms of orders of magnitude, the recharge estimate can hardly be more precise. The Darcy equation should therefore be used to check results rather than to base direct estimations on it.

2.2 Backward estimation

Any backward estimation is based on analysing the effects of groundwater recharge, such as groundwater level fluctuations and isotopic or hydrochemical properties. Also the analysis of stream flow data can be used provided that the underlying assumptions of this method are met and that the contribution from aquifer discharge can be separated with adequate methods.

2.2.1 Base flow analysis

If – due to the geological conditions – the total amount of groundwater re-appears as spring flow, the recharge can be derived from the base flow. A discharge separation is required. After the separation of groundwater outflow from the stream flow, the groundwater flow is integrated. This method is based on the assumptions that a) there exist steady state conditions and b) that deep percolation is negligible or known. *Therefore it is only applicable in adequate geological conditions that correspond to these assumptions.* Daily stream flow data is needed.

2.2.2 Groundwater level fluctuations

Groundwater level fluctuations indicate the response of an aquifer to groundwater recharge and can be de-convoluted to recharge time series.

For a homogeneous, unconfined aquifer the proportionality factor between groundwater level changes and recharge is given by the effective porosity *p* of the column affected by groundwater level changes. High seasonal variability of rainfall and distinct recharge events facilitate the isolation of water level rises induced by groundwater recharge. While recharge is characterized by episodic events, natural water losses occur continuously. During periods when the rate of recharge approaches zero, water level decline reflects the net lateral groundwater flow (Figure 2). The difference between predicted and actual groundwater levels can be transformed into recharge, if the effective porosity is known and constant for the range of water level changes. Problems arise from deviations of the basic assumptions (zero flow conditions) and from the difficulty to determine the porosity.

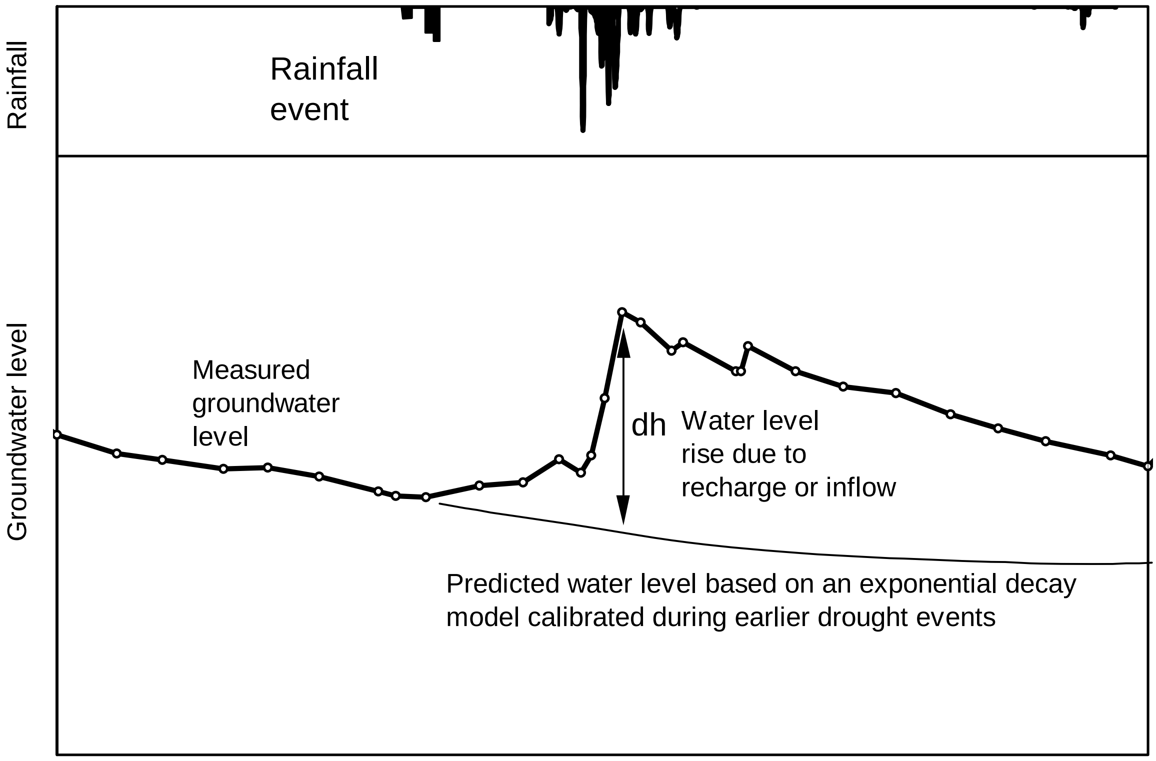


Figure 2 The water level fluctuation method: during periods without recharge (dry seasons) the water level decline is modelled and a predicted water level without recharge is computed. The deviation of the observed water level from this value represents the sum of lateral subsurface inflow and of recharge by percolation.

2.2.3 Groundwater flow models

Groundwater flow models are used to numerically solve the saturated flow equations. The specification of groundwater recharge is one of the boundary conditions. It has been proposed to use groundwater recharge as a fitting parameter and to derive recharge rates from groundwater flow models. This method can only yield reliable results if the conceptual flow model and the other parameters used in the groundwater model can be determined with accuracy. Often, the other parameters such as aquifer thickness, porosity, leakage factors, lateral inflows or hydraulic conductivity can only be roughly estimated or are not known - this affects the reliability of the recharge estimations derived from such models. In fact groundwater models require recharge estimations based on independent methods. In a following step, they can be used and represent a good tool for *validating* regional recharge estimates.

2.2.4 Isotope methods for groundwater recharge estimation

Isotopes can be used in different ways for the backward estimation of groundwater recharge. It is useful to distinguish methods characterizing the recharge process in the unsaturated zone and methods that are based on isotope analyses of groundwater. The advantage is that they give measured evidence and that isotope methods yield time and space integrated information: Processes over longer time periods and larger areas are averaged by mixing processes. For the interpretation of results it is important to correctly represent these mixing processes.

2.2.4.1 Oxygen-18 time series investigations

Oxygen-18 time series can be used to identify very young groundwater components. Since the signal of oxygen-18 is changing seasonally and converges to a stable weighed average, changes in oxygen-18 in time indicate a young recharge component.

2.2.4.2 Age determination along flow paths

Age indicators, such as tritium, carbon-14, krypton-85, fluorinated hydrocarbons (FHC) can be studied along flow paths. From the ‘ageing’ of groundwater along flow paths, the flow velocity can be estimated. The advantage of these methods is that they yield measured evidence whether the ground water is young and has a high turnover or whether it is old having a slow turnover and being well protected against pollution. Difficulties can arise from not considering the hydro-geological conditions and from neglecting borehole effects.

An overview of the most common methods is given in table 1 (next page). This table also lists the data requirements, the optimal climatic and geologic realm of application and further advantages and disadvantages. Finally, the expected results are presented.

Name of method	Time scale			Spatial scale			Climatic Realm				Geo-Environments				Recharge types covered		Required field work				Required Data							Available Software			Applications in Brazil				Results				
	< 1 year	1-50 years	> 50 years	Local	Basin	Regional	Tropical	Humid	Semi-arid	Arid	Sediments	Hard-rock	Karst	Human impact	Direct	Indirect	Reconnaissance	Sampling	Measurement	Construction	Rainfall	Runoff	Water levels	Aquifer data	Landuse data	Isotopes	Chemistry	Standard (Spreadsheet)	Commercial	Scientific	a. Local application	b. General GAS study	c. Operational method	Not documented	Discrete Time Steps	Discrete Grids (Maps)	Transfer to side-basins	Parametric method	Allows Scenarios
Experimental methods																																							
Lysimeter	+	-	-	+	-	-	+	+	o	-	+	-	-	o	+	-		o	+	+	+	-	-	-	+	o	o	-	-	+	1	-		+	+	-	+	-	-
Tensiometer	+	-	-	+	-	-	o	+	o	-	+	-	-	o	+	-	-	+	+	+	+	-	-	-	+	o	o	-	+	+	2	-			+	-	-	-	-
Soil water balance																																							
Soil water balance	+	o	-	+	+	o	+	+	o	-	+	-	-	+	+	-	+	-	-	-	+	+	+	+	+	-	-	o	o	+	3				+	+	+	+	+
Chloride method	o	+	O	+	o	-	-	o	+	+	+	+	+	o	+	+	+	+	+	-	+	-	-	-	-	-	+	-	-	+	4			+	+	-	-	+	-
Hydrologic water balances for different balance units																																							
Water works data	+	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	-	-	-	+	-	-	-	-	+	-	-	5				+	-	-	-	o
Spring discharge	+	-	-	+	+	-	+	+	o	-	+	+	+	+	+	+	+	-	+	o	o	+	-	-	-	-	-	+	-	-	6				+	-	-	-	-
Base flow	+	+	O	o	+	o	+	+	+	-	+	+	+	+	+	+	+	-	+	-	+	+	-	-	-	-!	-!	+			7a	7b	7c		+	-	-	+	-
Aquifer parameters and storage changes																																							
Water level change	+	+	-	+	+	o	+	+	+	+	+	o	o	+	+	+	+	-	+	-	+	-	+	+	-	-!	-!	+		+	8				+	o	-	+	-
Aquifer data (Darcy)	-	+	+	-	+	o	+	+	+	o	+	o	-	+	o	+	+	-	-	-	-	-	+	+	-	-!	-!	+			9a	9b			-	-	-	o	-
Aquifer model	o	+	+	o	+	o	+	+	+	o	+	+	-	+	+	+	+	-	+	-	-	+	+	+	-	-!	-!		+		10a	10b			+	+	-	o	+
Isotope and hydrochemical methods																																							
^{18}O stable isotope time series	+	-	-	o	+	o	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	-	-	-	+	o	-	-	+	11				+	-	-	-	-
Tritium, ^{85}Kr, FHC, SF_6, other tracers	-	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	o	o	-	+	o	+	+	+	12				-	-	-	+	o
^{14}C dating / mixing	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	o	o	-	+	o	+	+	+	13				-	o	-	+	o
Development of hydro-geological concept models																															14a	14b	14c						

Table 1 Overview of the most common methods for groundwater recharge estimations and their properties

3 State of the art of recharge studies on the Guarani Aquifer System and in Brazil

An extensive literature review was carried out listing the available studies in Brazil. These studies were analysed and summarized for the first meeting in São Paulo. The available recharge methods have been classified according to the table above into (1) experimental methods, (2) soil water balance methods, (3) groundwater balance methods, (4) methods based on aquifer parameters and Darcy's law and finally (5) isotope methods. The table of recharge methods also indicates which type of results are to be expected and which data are required.

The overview indicates that the following methods are dominant:

- methods based on aquifer parameters with 14 documented and published studies
- soil water balance methods with 8 documented and published studies,
- base flow analysis studies with 6 documented and published studies

The use of groundwater models still represents a scarcely used tool. The few applications of groundwater models did not always yield applicable results.

The following methods have only be used scarcely but are documented and published:

- Tensiometers (due to local scale relevance in agro-hydrological studies only)
- Water works data analysis
- Tritium, ^{85}Kr, CFC, SF_6, Carbon-14 studies and other tracers

Few recent systematic studies on hydro-geological conceptual model development were found (see Strugale et al., 2002).

No documented and published works have been found on

- lysimetres
- chloride method (which will hardly yield results anyway due to low chloride input)
- spring discharge as balance method for small catchment areas
- oxygen-18 time series method for indirect and localized recharge
- water level changes according to the 'de Marsily-method of de-convolution' (probably due to feared interference with pumping draw-down or missing data)

References to Table 1 'Recharge methods and their properties'

1) *Lysimeter*
-
2) *Tensiometre*
Gloeden, E. (1994) [S. Paulo State]
3) *Soil water balance*
Camargo, A.P. (1978) [S. Paulo State with map]
Souza, A. et al. (1979) [S. Paulo State]
Souza, A.; Sinelli, O.; Davino, A. (1982) [[S. Paulo State - Cravinhos]
Ometto, J.C.; Villa Nova, N.A. (1986) [S. Paulo State]
Matos, Ivone da Silva (1987) [S. Paulo State]
Braga, B.P.F.; Conejo, J.G.L.; Palos J.C.F. (1991) [S. Paulo State]
Contin Neto, D. (1996) [S. Paulo State - Riberao Preto]
Pompêo, C.A. (1994) [St. Catarina State]
4) *Chloride method*
-
5) *Water works data*
Pfeiffer, S.C. (1993) [S. Paulo State]
6) *Spring discharge*
-
7) *Baseflow*
a. Souza, A. et al. (1979) [S. Paulo State]
Piui, J.; Campos, H.C.N.S. (1984) [S. Paulo State, **Araraquara – Base Flow estimation and water balance]**
Corrêa, U.M.P. (1995) [S. Paulo State]
Oliveira, J.N. (2001) [S. Paulo State, Riberao Preto]
Pompêo, C.A. (1994) [St. Catarina State]
b. -
c. **Lopez, M.F.C. (1994) [S. Paulo State, Bauru – Baseflow estimation – operational method by DAEE]**
8) *Water level change*
-
9) *Aquifer data*
a. Souza, A. et al. (1979) [S. Paulo State]
Silva, R.B. (1983) [S. Paulo State]
Fraga, C.G. (1992) [S. Paulo State]
Corrêa, U.M.P. (1995) [S. Paulo State]
Rosa Filho, E.F. et al. (1998/2000) [Parana]
Zanatta, L.C. & Coitinho, J.B.L. (2002) [St. Catarina State – Aquifer data, geometry]
Giardin, A. & Faccini U. (2002) [Rio Grande do Sul]
b. Reboucas, Aldo (1976) [GAS] [S. Paulo State]
Teissedre & Barner (1981) cited in Reboucas, A. (1981) [S. Paulo State]
Teisseidre, J.M.; Sanches, J.L.; Lopes, M.F.C. (1982) [S. Paulo State - Hydraulic parameters]
Reboucas, Aldo (1994) [S. Paulo State - GAS]
Chang, H.K. (2001) [S. Paulo State - GAS]
Campos, H.C.N.S. (2002) [Rio Grande do Sul, Lit. overview]
c. Rocha, G.A. (1997) [S. Paulo State - GAS – DAEE compilation of hydraulic data]
10) *Groundwater models*
Montenegro, A.A.A. et al. (1988/1989/1990) [S. Paulo State, Riberaio Preto]
Contin Neto, D. (1996) [S. Paulo State, Riberaio Preto]
11) *Oxygen-18 time series & investigations*
-
12) *Tritium, ^{85}Kr, FHC, SF_6, other tracers*
Gomes, M.A.F., Spadotto, C.A. (2001) [S. Paulo State, Rib. Preto – Agrochemical tracers]
Gomes, M.A.F.; Filiozola, H.F., Spadotto, C.A. (2002) [S. Paulo State, Rib. Preto – Agrochemical tracers and recharge areas]
13) *Carbon-14 dating and mixing models*
Silva, R. B.G. (1983)
14) *Development of hydro-geological concept models*
Strugale, M. et al. (2002) [Parana – development of a structural model and concept based on water levels]

The distribution of documented works depends also on the scale of the application. For local scale applications, the soil water balance method was found to be dominant. Other possible methods using water works data, water level changes or isotopes have not been used at a broader scale yet.

For regional scale applications the most common method applied in Brazil is the base flow analysis with special reference to the method and model of Mero. Other methods such as the use of lumped or distributed soil water models, water works data, groundwater level changes, groundwater models or the use of dating techniques is documented in some studies but still less common.

Applications for the GAS aquifer as a whole are mainly based on aquifer parameters. Groundwater models at this scale have been developed for the purpose of conceptual modelling and for the validation of general flow hypotheses.

4 Choice of method and computer models

The choice of methods takes into account several aspects that were considered in the survey of existing methods:

- Data availability
- Purpose of the study
- Time and spatial scale
- Formation of personnel (soil physics, hydrogeology, isotopes, chemistry, hydrology)
- Costs and infrastructure
- Type of recharge studies and geology, climate, vegetation or land-use

The soil water balance approach should be consolidated based on the existing work at the **meso-scale** (up to a few hundred km²) and **macro-scale** (up to a few thousand km²). Also the base-flow analysis is well established in Brazil. In some cases the base flow analysis has also reached the operational level, that is the application in state agencies and for planning purposes. The data availability was discussed at CETSB and at the Geological Insitute for point data (Figure 3, time-series) and for spatial data sets (Figure 4,a,b,c). Meteorological daily data for temperature, relative humidity, rainfall and even for some special parameters (sunshine hours, windrun) are available. However, the quality of discharge data in Ribeirão Preto is considered to be poor.

		disponibilidade disponivel = 1 externo & disponivel = 2 não existente = 3 ? = 4	fonte de dados	balanço de água no solo	Nível de água	Analise da discarga	isotopos	
meteorologia	chuva	2		x				
	temperatura	2		x				
	humidade	2		x				
	velocidade de vento	2		x				
	insolação diaria	2		x				
uso da terra	mapa temático	1,2 (~ escala)		x				
	ou imagem de satelite	1		x				
	mapa do solo	2		x				
	> capacidade de campo	3		x				
	> taxa de infiltração	3		x				
	mapa topográfico	1		x				
	(modelo digital do terreno)	1		x				
hidrologia	dados de discarga diaria	2,3 (~ do endereço)		x		x		
hidrogeologia	recarga (poço)							
	vazão	2.3			x			
	nivel de água	2?-3			x			
	porosidade efetiva	2?-3			x			
qualidade de água	ions maiores	1.2						
	pH, CE, T	1.2						
	traçadores antropogênicos	1.2					x	
	N, fosfato						x	
	pesticdas & herbicidas	2					x	
	CFC	3						x
	18O	3						x
	tritium	3						x
	14C	(2),3						x
	isotopos de cloro	3						

Figure 3 Estimation methods for recharge and data requirements (Portuguese)

At the Instituto Florestal, the software equipment (ArcView) and the spatial data with the following information exist and have been made available for the project:

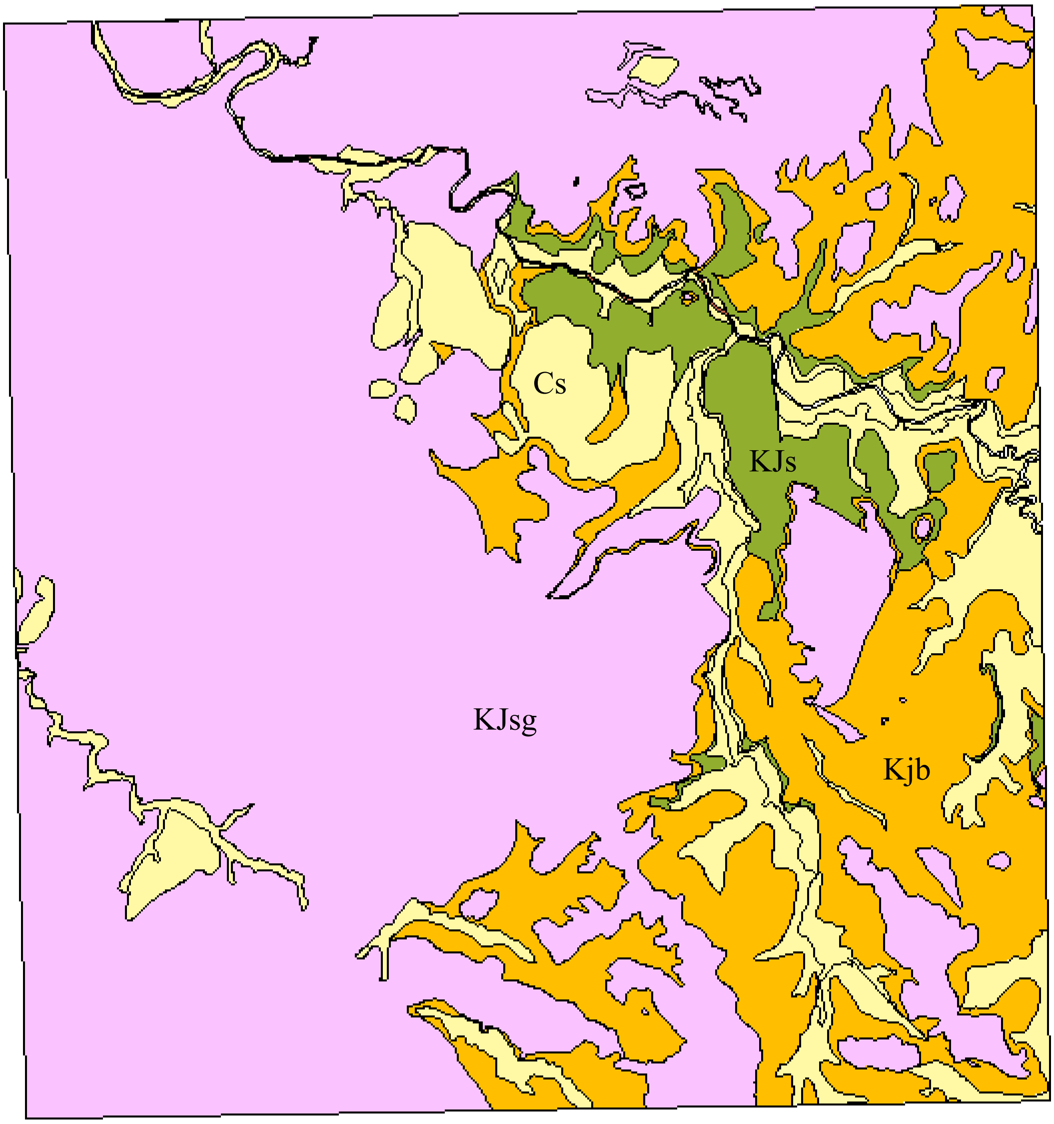
- ✓ *Digital elevation data as polygon shapes 1:50.000 with 20 m equidistance*
- ✓ *River network and reservoirs (open water surfaces)*
- ✓ *Geological Map 1:50.000 with faults*
- ✓ *Soil map 1:100.000 and detailed*
- ✓ *Land-use polygon with 10 classes*
- ✓ General layers with topographic information: roads, extent of urban area, railway lines

The datasets cover the needs for a distributed hydrological / hydrogeological model (in italics layers needed for common distributed hydrological model). The polygon shape can be transformed in a grid layer providing raster digital elevation data (DEM) and slope for the infiltration, evaporation and runoff generation modules of soil-vegetation-atmosphere-transfer (SVAT) models. The watershed delineation can be generated from the DEM.

The geological map, soil map and land-use map provide the necessary data for the spatial parametrisation. The geological map contained the formations, the lithology and a description of the formations. The geology controls – together with the climate, the vegetation and the topography – the development of soils and their texture. The weathering process produces typical soil textures. Complete weathering of basalt and of diabase results in clayey soils, the weathering of the Botocatu Formation produces soils in which the content of sand is higher. As a consequence, the geological map is important for the interpretation of the soil map.

The soil map contained soil texture and soil classes. The available soil map is using a morphologic and partly genetic description of soils, referring to the texture and development of soils. The hydraulic properties need to be inferred from the additional information on soil texture and from the geology (see above).

The land use map contained a land use classification with 12 classes. The dominant land use type is secondary vegetation characterised by agricultural use of the land. Although the main type of land use is known (sugar cane), the actual distribution of plots and of crops was not known. It was beyond the scope of this investigation to get such information. However, for further more detailed studies it is important to include the land use practices and agricultural techniques.



	Cs	Cenozoic	unconsolidated sand
	KJsg	Serra Geral	basalt
	KJs	Basic intrusives (sills)	diabase
	Kjb	Botocatu Formation	well sorted aeloian sand

Figure 4a Selected themes of the spatial dataset provided by Instituto Florestal: geology

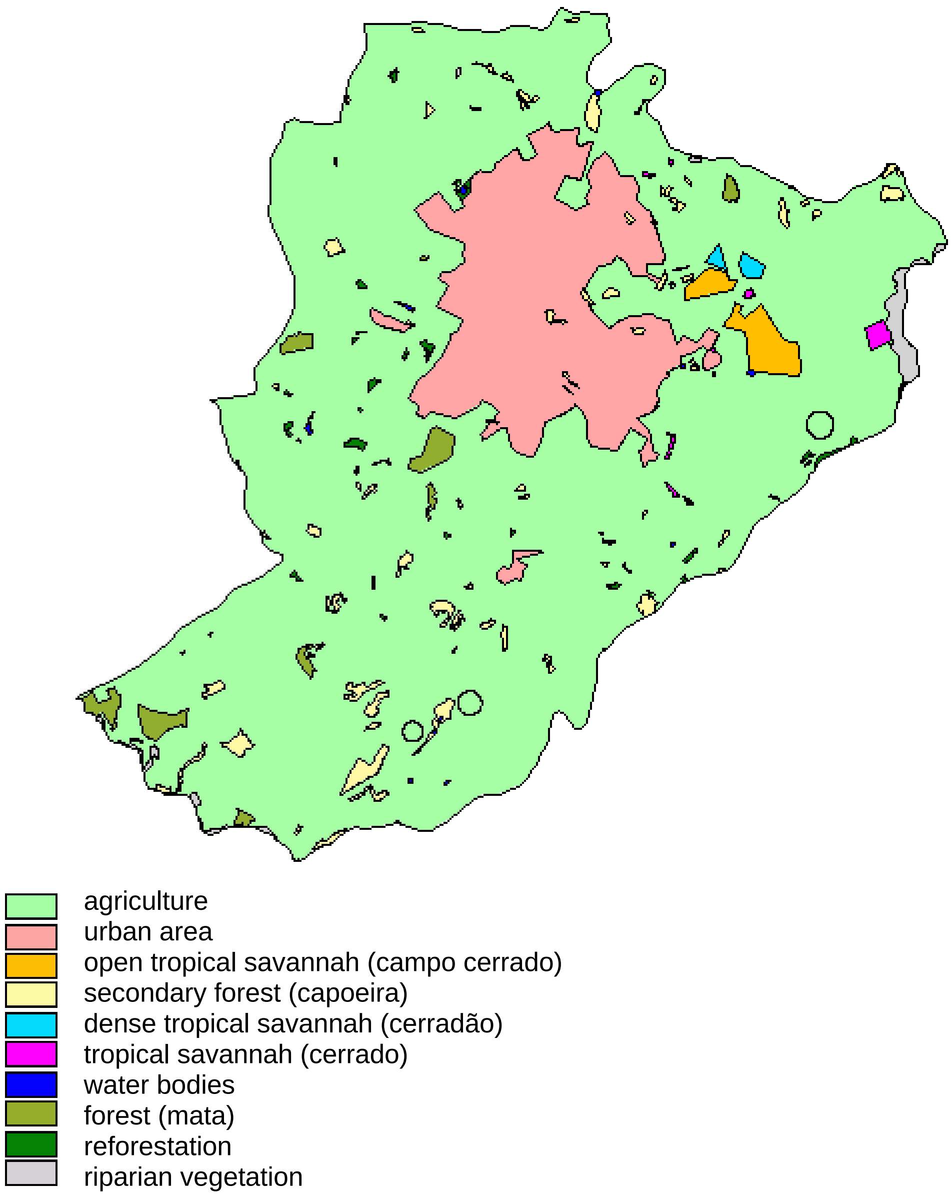
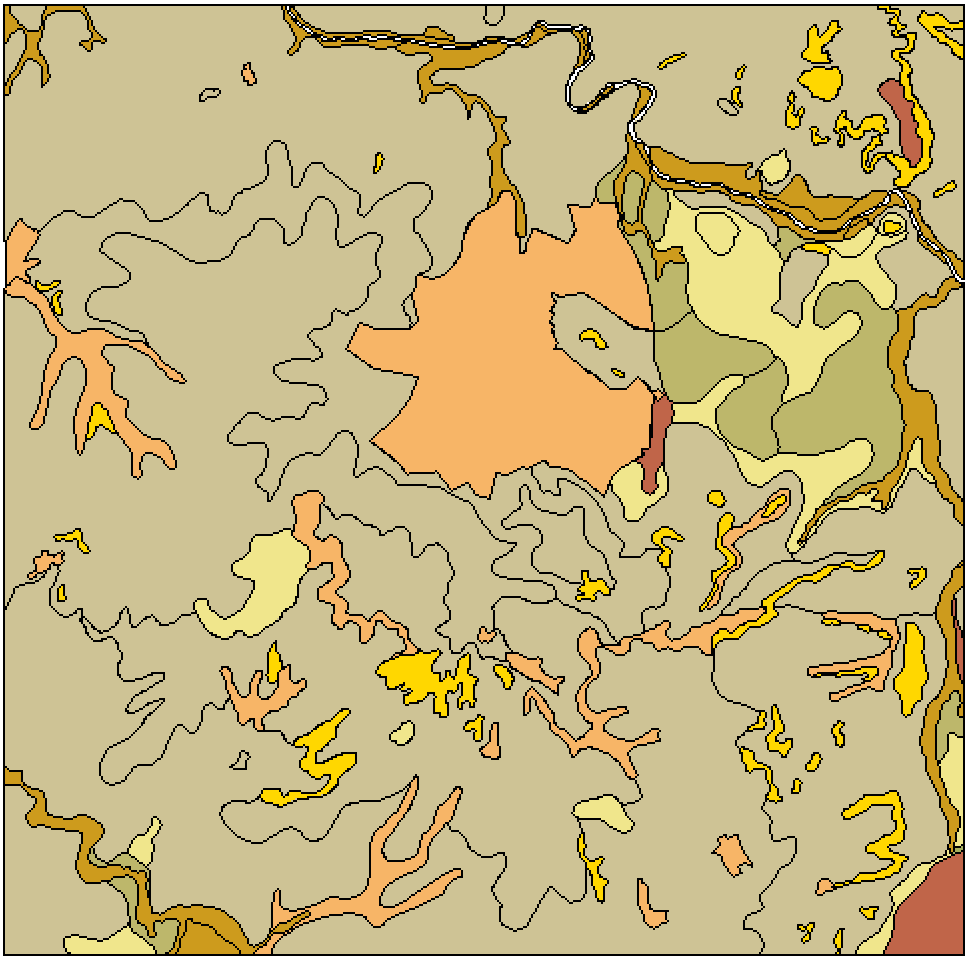


Figure 4b Selected themes of the spatial dataset provided by Instituto Florestal: land use



1	*AQ*	*sandy texture along the profile (lS)*
2	*Li+TE*	*Chernosem, clayey texture +/- stony and Terra Rossa (sL)*
3	*LV+AQ*	*Deep sandy soils (slS)*
4	*TE*	*Latosols (lC)*
6	*LRd*	*Soil with clayey texture, aggregateted (L)*
7	*Lra*	*Soils on alluvial material / hydromorphic (lC)*
9	*LE*	*moderate A horizon, clayey texture (lC)*

Figure 4c Soil types in the study area, data provided by Instituto Florestal

The result of the comparison of available data with the data needed for running different methods, suggested the following approach: A climatic and soil water balance should be established for selected point locations with a SWAT (soil water atmosphere transfer) model. This model should be extended to the regional scale with a distributed soil water balance model. The software should be cost free and open source. The baseflow method can not yield an independent recharge estimation. This method is used for a validation and balance check.

Among the many existing SWAT models, two were chosen for the project. **AVSWAT-2000** is an ArcView extension and a graphical user interface for the SWAT (Soil and Water Assessment Tool) model. SWAT is a river basin, or watershed, scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient, uses readily available inputs, and enables users to study long-term impacts. For a detailed description of SWAT, see Soil and Water Assessment Tool Theoretical Documentation and User's Manual, Version 2000 published by the Agricultural Research Service and the Texas Agricultural Experiment Station, in Temple, Texas. The SWAT model can be applied to support various watershed and water quality modeling studies. SWAT is being used extensively in the U.S. and Europe to assess the impact of global climate on water supply and quality.

ArcView provides both the GIS computation engine and a common Windows-based user interface. AVSWAT is organized in a sequence of several linked tools grouped in the following eight modules: (1) Watershed Delineation; (2) HRU Definition; (3) Definition of the Weather Stations; (4) AVSWAT Databases; (5) Input Parameterization, Editing and Scenario Management; (6) Model Execution; (7) Read and Map-Chart Results; (8) Calibration tool. Once AVSWAT is loaded, the modules get embedded into ArcView, and the tools are accessed through pull-down menus and other controls, which are introduced in various ArcView graphical user interfaces (or GUIs) and custom dialogs. The basic map inputs required for the AVSWAT include digital elevation, soil maps, land use/cover, hydrography (stream lines), and climate.

The second model is **REGIS** developed by the author. This model is used for training purposes and point estimation of recharge. This model has been applied in Europe and in Brazil within the project WAVES – it represents the same physical processes as AVSWAT 2000. The model calculates interception losses, runoff generation, soil moisture storage, inter-flow and groundwater recharge. It requires meteorological data and soil/aquifer parameters.

Meteorological parameters	***Topographic, soil and bedrock parameters***
Rainfall	Elevation, slope
Temperature	Infiltration and field capacity
Relative humidity	Bedrock permeability

As meteorological parameters, daily rainfall, temperature and relative humidity are needed. As soil and bedrock parameters, elevation, slope, infiltration and field capacity and the hydraulic conductivity of the layer below the soil are required. The atmospheric evaporation demand has been calculated using an approach proposed by Priestley & Taylor (1972). This method incorporates an energy term and uses humidity and temperature data. The downward movement of soil water (percolation) is a function of soil moisture state according to the relationship v=K(q), where K(q) represents the unsaturated hydraulic conductivity K for a soil wetness q. The term K(q)/K corresponds to the ratio of unsaturated to saturated hydraulic conductivity and has been determined according to Van Genuchten. The model includes a simple representation of macropore flow, which is expressed as a fraction of surface runoff. The model also provides the possibility to calculate river discharge. River discharge is modelled as a combination of direct and fast surface runoff and of base-flow from aquifer outflow. Aquifer outflow is linked to the water level in the aquifer by an exponential law in the form qt = q exp(-at), where qt is baseflow, q baseflow at the previous time step, α corresponds to a recession constant and t to the chosen timestep.

5 Results

In this chapter the development of the conceptual model, the isotope data and the water balance calculations are discussed.

5.1 Hydrogeological model

Jointly, a hydrogeological model for the study area of Ribeirão Preto was developed. Hydrogeological models help to specify, clarify and synthesize the (hydro-)geological information for a given study area. A hydrogeological model shows and represents the parameters and processes that are relevant for a study in a given region in a schematic way. In fact, the conceptual hydrogeological model is the definition of the system boundaries, properties and processes according to the specific tasks to be carried out (FACHSEKTION HYDROGEOLOGIE IN DER DEUTSCHEN GEOLOGISCHEN GESELLSCHAFT, 2002).

The conceptual model was developed jointly during three project meetings in December 2002, April 2003 and June 2003. It is based on the state of the art geological information obtained from our partners in Brazil and on additional information from a field trip in December 2002. An important element of the development and verification of the conceptual model have been isotope investigations in the area of Ribeirão Preto that have been carried out in summer 2003.

5.1.1 Information from the common field trip

The field trip covered the crystalline basement, the Corumbataí Formation (Frm.), the Piramboia Frm., the Botucatu Frm., the Serra Geral basalts and Diabase as well as the type locality of the Bauru Frm. In the field several aspects of the groundwater flow, balance and conceptual model especially the possibility of recent or actual upward flow from the formations underlying the Piramboia Formation was discussed at a location with fractures and fracture fillings.

Fracture fillings of calcite in the *Teresina Formation* indicate that seepage losses at the base of the Piramboia Frm. are not significant. Downward seepage from the overlying sandstone formations would dissolve calcite.

The *Piramboia Frm.* itself was found to be fine-grained, having a silty-sandy composition. This formation acts as a groundwater storage with low hydraulic conductivities, dual porosity is possible. In some locations iron leach-precipitation patterns were found indicating an interface between fresh groundwater (recharge Botucatu) and reduced groundwater within the Base of the Piramboia Frm.

The *Botucatu Frm.* due to its deposition is composed of well sorted iron-oxide cemented sand. In places, the Serra Geral Frm. was found to have – compared to the Botucatu and Piramboia Frm. – rather shallow soils allowing high recharge rates and a fast percolation.

The thickness of soils is an important recharge parameter, its regionalisation has been a crucial step in the recharge estimation. Therefore, it has been observed in the field and described in the conceptual model explicitly. The outcrops of Serra Geral are covered by soils of variable thickness, overlying basalt and diabase with strong, also horizontal fracturing; fractures have been found to be water bearing. The relevance of the basalts for the groundwater balance was highlighted from the observations in the field. The greater soil thickness of the Botucatu and Piramboia Frm. lends to comparatively higher water storage in the soil and increased evapotranspiration.

5.1.2 Consolidation of existing knowledge

The major elements of a water balance are (Figure 5):

- direct recharge in the recharge zone (outcrops of Botucatu Formation) - $\mathbf{R_{Db}}$,
- effluent conditions and baseflow losses - $\mathbf{Q_{Bf}}$,
- direct and indirect recharge (influent stream sections) through the Serra Geral Frm. with a preferential flow component reaching the Botucatu Frm - $\mathbf{R_{Dsg}}$.
- possibility of upward flow from the underlying Piramboia Frm. $\mathbf{R_{UL}}$
- Outflow from the system $\mathbf{Q_{out}}$
- pumpage **P**

Fracture fillings of calcite in the Teresina Frm. indicate that seepage losses at the base of the Piramboia Frm. are not significant. Downward seepage from the overlying sandstone formations would dissolve calcite. However, these processes can vary regionally and require potentiometric maps from both aquifers to be answered precisely. The system has been exposed to tectonics, creating blocks that have been moved towards each other. The flow system also depends on the juxtaposition of these blocks and on whether these faults are hydraulic pathways or hydraulic barriers. A detailed geotectonical analysis could supply a clearer picture about the function of the different faults and joints.

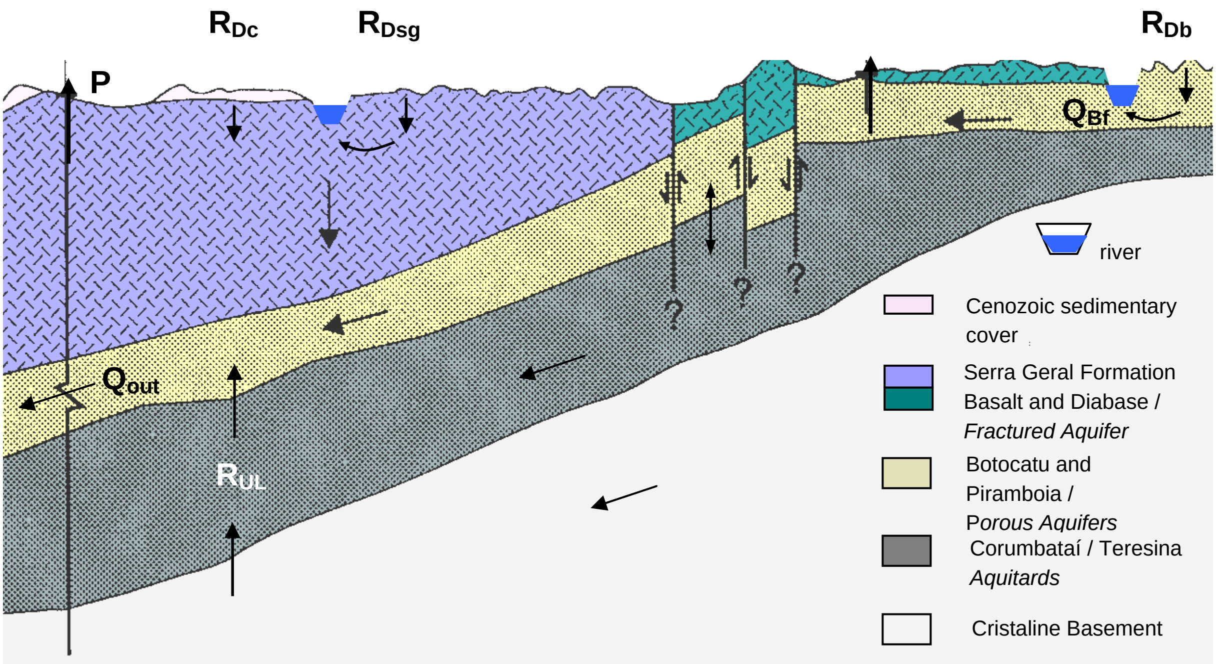


Figure 5: Scheme showing the major flow paths and processes in the study area

Any conceptual model building and future models of groundwater flow need to include the possibility of a system of cells and blocks corresponding with each other. It is also possible that blocks have been disconnected from the regional flow system and expose hydro-chemical singularities. There is a lack of conceptual model building. This implies the use of monitoring activities for water levels and the collection of hydro-chemical and isotope data. Therefore, isotope investigations have been carried out.

5.2 Isotope investigations

Isotope investigations on stable isotopes (^{18}O, ^{2}H) and radiocarbon (^{14}C) by GALLO & SINELLI (1980) in the study area. The data collected within this study indicate tritium levels below 5 T.U., enrichment for analysis down to less than 1 T.U. was not yet carried out. ^{14}C data in the confined area gave apparent ages from which travel times of about 1.4 m/y between Ribeirão Preto and Sertãozinho were estimated. Within the project, isotope samples have been taken in April/May 2002 in the study area in order to get additional information sustaining the conceptual model. The isotope analyses were also carried out to get information on recharge processes and on groundwater ages that allow a verification of estimated groundwater recharge rates. Altogether 10 samples were taken and analysed for tritium (^{3}H), oxygen-18 (^{18}O) and deuterium (^{2}H) (see table 2). The samples were taken from wells that penetrated the Serra Geral and the Botocatu Formations. The pH of the groundwater was below 7 ranging between 5.2 and 6.6. The temperature ranged between 23.3 °C and 26.0 °C corresponding to the main annual temperature. For carrying out an interpretation of the stable isotopes ^{18}O and ^{2}H the recent input from rainwater was needed as a reference. For this purpose IAEA rainfall data for Rio de Janeiro. from the Global Network of Isotopes in Precipitation was downloaded from the IAEA-GNIP database. Rainfall along the Southern South American coast plots on a local meteoric water line.

Table 2: Isotope investigations in the area of Ribeirão Preto

Laboratory number	Borehole name	pH	temp. °C	Date	^{3}H T.U.	^{3}H error T.U.	$\delta\,^{18}O$ ‰	$\delta\,^{2}H$ ‰
146295	P101	6.12	24.3	5/ May/ 03		<0.6	-7.02	-48.9
146296	P114	5.34	23.3	6/ May/ 03		<0.6	-7.48	-49.2
146297	P115	5.64	23.7	6/ May/ 03	1.0	2.4	-7.12	-45.6
146298	P135	5.47	24.7	6/ May/ 03		<0.6	-6.85	-46.7
146299	P140	6.60	23.5	5/ May/ 03	0.9	1.5	-7.02	-48.8
146300	P167	6.33	25.4	6/ May/ 03		<0.6	-7.60	-50.7
146301	P168	6.15	25.4	5/ May/ 03		<0.6	-7.16	-46.5
146302	P171	6.09	26.0	6/ May/ 03		<0.6	-6.82	-47.6
146303	P176	5.23	23.7	6/ May/ 03		<0.6	-7.52	-47.9
146304	P180	6.20	24.0	5/ May/ 03		<0.6	-7.40	-50.5

The stable isotopes of the groundwater samples plot on the local meteoric water line of Rio de Janeiro that lies well below the global meteoric water line (see Figure 6). The grey dots indicate rainfall samples (IAEA), the filled blue and orange dotes indicate groundwater samples. The orange dots have also been analysed for tritium, for the blue dots just stable isotope data exists. The groundwater samples are clearly more depleted than the average of the rainfall samples.

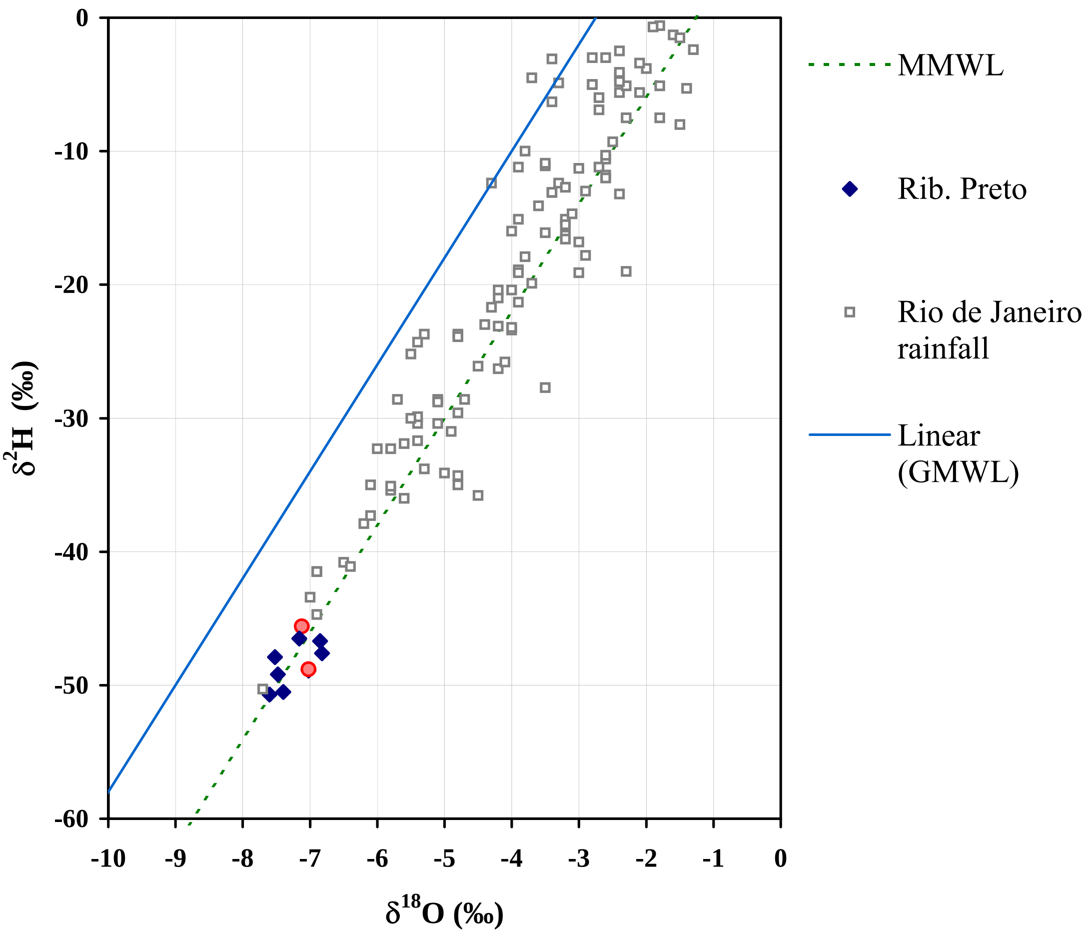


Figure 6 Stable isotopic composition of groundwater in the study area

The analysis of the rainfall time series of the reference station Rio de Janeiro shows that the lightest precipitation falls during January, February, March during the rainy months that coincide with higher temperatures. The groundwater samples correspond to the lightest rainfall samples that fall during these months.

The local meteoric water line helped to classify the groundwater samples. A downward deviation from the local meteoric water line would indicate evaporation processes. If the samples plot on a completely different line, this indicates recharge under different meteorological conditions.

The groundwater samples do not show any obvious effects of evaporation or of a climatic shift. This finding is also supported by the fact that the deuterium excess of all samples is close to + 10 ‰ which is typical for rainfall that has not undergone evaporation during the recharge process.

Tritium has been measured for all 10 samples. Only in two samples – borehole P115 and P140 – detectable tritium was found. Both boreholes are located close to the outcrop areas of the Botocatu Frm.

All samples have been measured after electrolytic enrichment. The detection limit corresponds to about 0.5 tritium units. In Figure 7 the input function for Rio de Janeiro is shown. Although the input function is only known until 1985 and although some data are missing, Figure 7 shows that the tritium peak does not exceed 300 tritium units. Already in 1975 the tritium activity in rainfall dropped to about 10 tritium units. This has implications for the estimation of groundwater ages. Tritium can be used to detect young groundwater (< 50 years) only if the proportion of younger groundwater is significant.

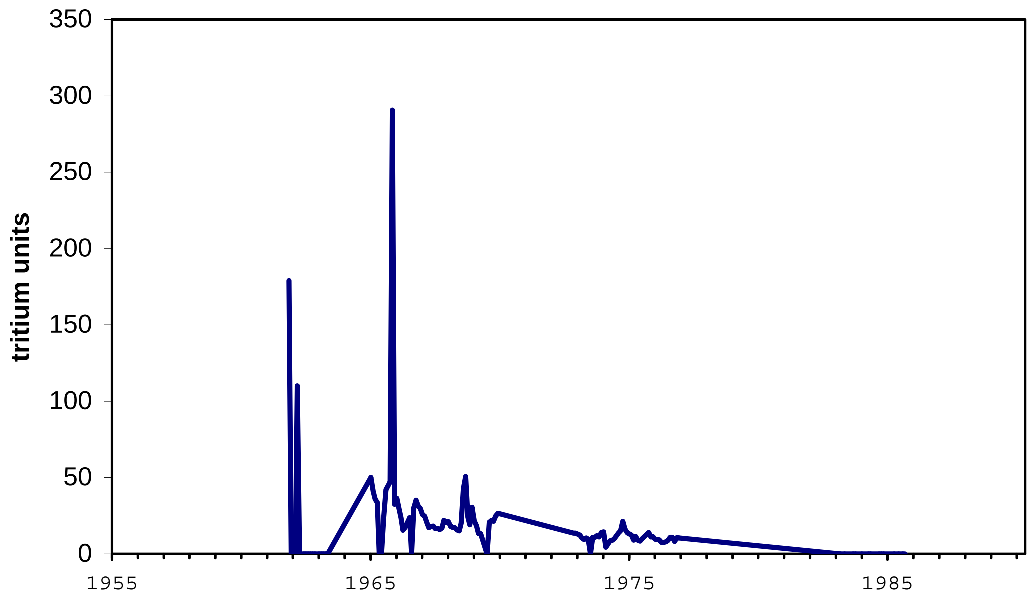


Figure 7 Input function of tritium in rainfall measured at an IAEA station in Rio de Janeiro

The presence of tritium in two samples close to the outcrop area of the Botocatu shows that the system is actively being recharged. The absence of tritium in the other samples mainly taken from boreholes with confining Serra Geral Formation (Basalt, Diabase) does not signify that in these areas recharge is absent. The absence of tritium *constrains* the proportion of groundwater that is contributing to the water balance of the Botocatu Formation.

In order to establish a quantitative water balance for the study area, a water balance model was developed. In this model, the land-use and soil parameters were specified explicitly. Using daily time-series of meteorological data, the soil water balance was calculated for a fine grid covering the study area. The results of these calculations are discussed in chapter 5.3.

5.3 Water balance modelling

The hydrological processes have been simulated with a recent version of the water balance model REGIS. Any water balance approach requires a definition of a hydrological system for which the individual components of the hydrological cycle are balanced. 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. In the present study the water balance has been solved for each vertical column of square grids representing the study areas‘ soil and vegetation parameters. 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 two categories of data:

a) Time series data: time series of meteorological data such as
   i. Rainfall
   ii. Temperature
   iii. Relative humidity
b) spatial parameters
   i. elevation (see Figure 10)
   ii. slope (see Figure 11)
   iii. parameters of land-use (see Figure 4b)
   iv. soil type with
      1. hydraulic conductivity of the soil (derived from soil classes)
      2. field capacity of the soil (derived from soil classes)
   v. thickness of the soil (see Figure 12)
   vi. hydraulic conductivity of the sub-soil (see Figure 13)

Daily rainfall amounts are first reduced by interception on leaves. The interception capacity is derived from land-use types. In the actual version of REGIS 12 land-use types are distinguished. Interception storage is consumed by daily actual evaporation (for the calculation of evaporation, see below). Rainfall exceeding interception storage and initially intercepted rainfall that has not been evaporated after one day becomes canopy throughfall and contributes to *effective rainfall* reaching the soil surface.

REGIS processes raster / grids of the spatial data. For each grid cell a distance-weighted average of daily rainfall is computed. At the same time a distance-weighted average of station elevation is produced. Comparing this estimator to the actual topographical elevation an additional altitude correction is made using a regional rainfall/elevation gradient. The reduction of relative humidity with increasing elevation is accounted for by a topographical correction.

At each raster element, the soil is characterized by the elevation, slope, surface permeability (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 6 classes from kf_1 to kf_6. Infiltration takes place as long as the effective rainfall (the sum of snow melt and throughfall) is smaller than the infiltration rate of the soil. The infiltrated water is stored up to maximum effective field capacity in the soil matrix. Runoff is produced a) if the effective rainfall intensity is larger than the infiltration rate or b) if the effective field capacity has reached a maximum value. The effective field capacity represents the capacity of the soil to hold water against gravity that can be used by plants. The effective field capacity strongly depends on pore-size distribution and on the thickness of the root zone.

Values for infiltration rates and effective field capacity are estimated. The water movement within the soil is controlled by the atmospheric evaporation demand and by the moisture distribution in the soil. The atmospheric evaporation demand is calculated by two alternative methods. An empirical method for the calculation of potential evaporation or a parametrized physical approach according to Priestley & Taylor are used for the estimation of potential evaporation. The later method incorporates an energy term and uses humidity and temperature data.. The ratio between actual evaporation by plant transpiration and direct soil evaporation depends on the soil moisture state. The drier the soil, the lower actual evaporation rates become. The upward (transpiration demand) and downward movement of soil water (percolation) are expressed as a function of soil moisture state according to the relationship $r=K(\theta)$, where $K(\theta)$ represents the unsaturated hydraulic conductivity K for soil water content θ.

The model provides the possibility to calculate recharge rates and baseflow. Baseflow is linked to the storage in the aquifer by the classical law of Maillet [10] $q = q_0 \, exp(-a\, t)$, where *q* is actual baseflow, q_0 baseflow at the previous time step, *α* corresponds to a recession constant controlling the differential outflow and *t* to the chosen timestep. Leakage through the aquifer base if accounted for using Darcy's law and porosity.

5.3.1 Data preparation – time series data

For the model REGIS all the time series data (meteorology) and spatial data sets have been prepared. The preparation of the time series data included rainfall, relative humidity, and temperature. The data set extends from the 1st of January 1996 until the 31st of December 2001. Using the model REGIS 1.0, the potential evaporation was calculated for the whole time period based on the approach of Priestley-Taylor, which is a modified Penman-equation. For the calculation of the potential evaporation and temperature and relative humidity (daily) were used.

The additional parameters sunshine duration and cloud indices were taken from handbooks. The rainfall and potential evaporation were used to calculate a water balance for every specified cell of the study area. For this step, input files of spatial data sets for the parametes (topography, land-use / vegetation, effective field capacity, hydraulic conductivity and sub-soil conductivity) were prepared. The preparation of these input files was done jointly with experts from CETESP and Instituto Geologico and Instituto Florestal during the second working meeting in São Paulo.

Figure 8 shows the elements of a climatic water balance based on meteorological data and a standard soil (loamy sand) with a typical vegetation. In the study area rainfall is highest during the warmer southern summer months October, November, December, January, February and March, the southern winter months April to September are comparatively dry.

The evaporation follows the seasonal distribution of rainfall and temperature: During the summer the evaporation is much higher than during the winter time. During the dry winter months, temperature is lower and the soil moisture storage is emptied. Hence, the actual evaporation drops as soil water supply is reduced due to higher flow resistance (higher soil suction heads). The actual evaporation reaches 6 to 9 mm/day from October to March – this is a high value of evapotranspiration. From April to September the actual evaporation drops significantly because the daily temperature is lower, rainfall and soil water storage are smaller.

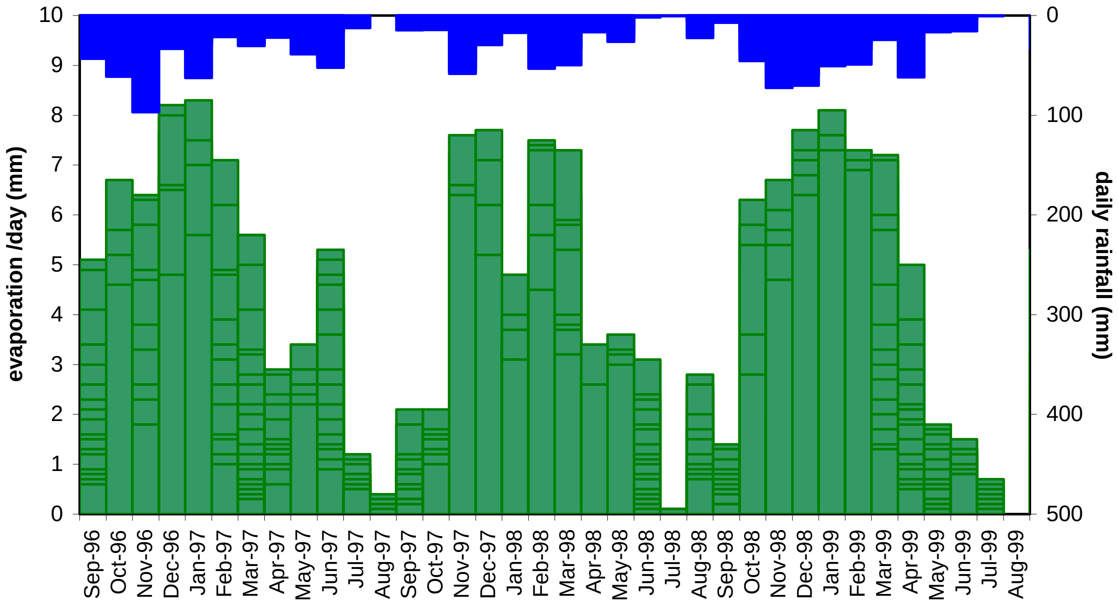


Figure 8 Average actual evaporation (green, left scale) and rainfall (blue, right scale) for the study area Ribeirão Preto based on rainfall, temperature and relative humidity for a reference soil 'loamy sand' with land-use type 'cerrado'.

The groundwater recharge distribution and the soil water dynamics follow this pattern as shown in Figure 9. During the rainy season, soil water storage increases and 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.

This results of the water balance modelling is confirmed by the stable isotope measurements – the composition of the groundwater corresponds to the composition of the lightest rainfall in the summer months December / January and February. This rainfall contributes selectively to the replenishment of the aquifer. Rainfall in the earlier part of the season are consumed by the plants and refill the field capacity of the soils. Rainfall in the later part of the season is not sufficient to exceed the recharge threshold – most of the water is kept in the soil and re-evaporates.

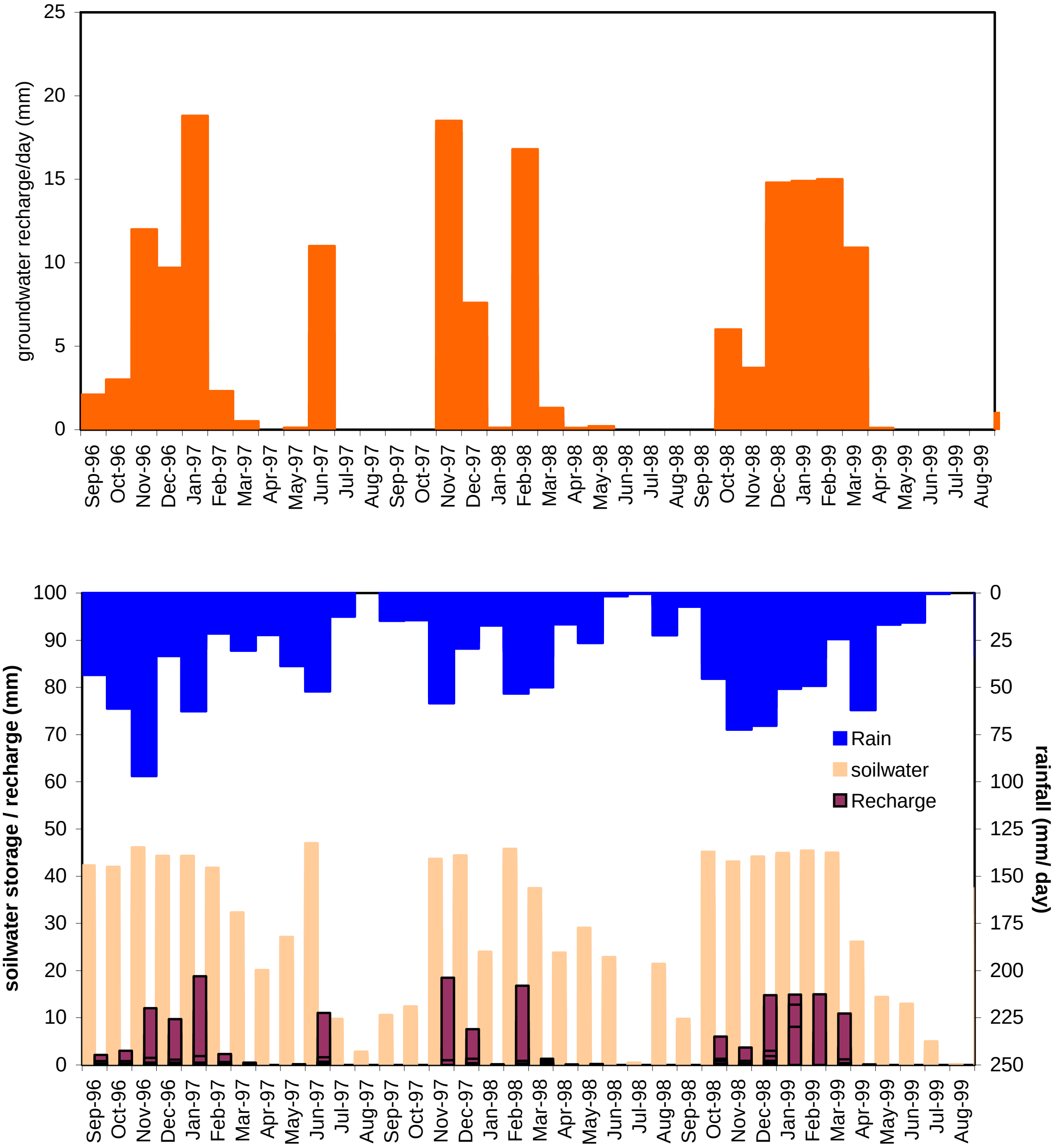


Figure 9 Typical recharge distribution and soil water dynamics in the study area Ribeirao Preto based on rainfall, temperature and relative humidity for a reference soil 'loamy sand' with land-use type 'cerrado'.

5.3.2 Data preparation – spatial data sets

For the study area the necessary data sets for water balance modelling have been prepared using GIS tools. These include as specified above topographic data (elevation, slope), land-use data and soil properties.

The input grids and the parameters will be described in the following. Elevation data (Figure 10) is needed to interpolate the meteorological data that is altitude dependent such as rainfall, temperature and relative humidity. From the meteorological station the rainfall grid is interpolated using a typical rainfall-altitude relationship. Also the temperature is adapted to the real elevation using the wet adiabatic function of a decrease of about 0.6 °C / +100 m.

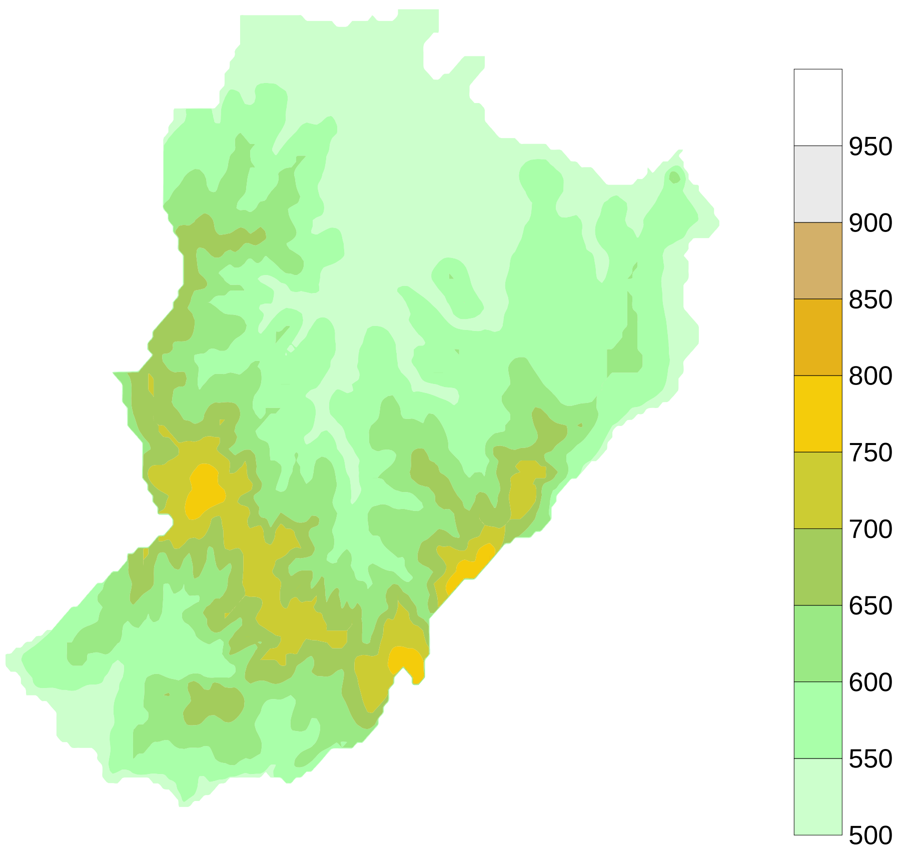


Figure 10 Topographic data and slope of the study area

The slope influences the generation of runoff: higher slopes produce more runoff. The influence of the slope on runoff is expressed through a slope-runoff function that can be modified through the program interface.

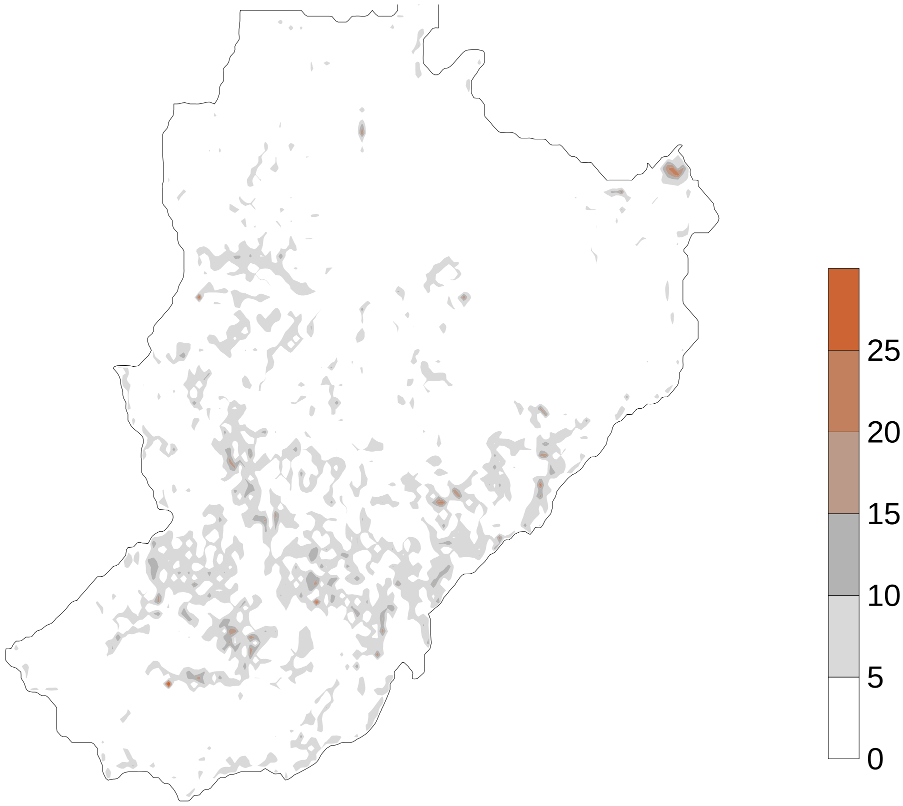


Figure 11 Topographic data: slope of the study area

Land-use and soil parameters have been re-classified. There are 7 different land use classes. The land use classes include water bodies (0), agriculture (1), young forest (2), urban areas (3) and different local types of natural vegetation such as cerrado (4), capoeira (5), mata (5) und cerradão (6).

The dominant land-use in the study area is agriculture. The second most important land-use is the sealed urban-area of Ribeirão Preto. The other land-use types 'mata', 'campo cerrado' etc. just exist in small patches and are of minor importance for the water balance.

Root-depths have been assigned for the different land-use types. The root depth is crucial parameter for the water balance estimation, since it controls the accessible water storage that can be evaporated by a plant. A grid with the root depth (m) has been prepared (Figure 12) that controls the depth of the soil water storage during the calculations. Water bodies have a 'large' root depth – this is too say that the supply of water is infinite and not limited by the soil water storage. The main difference between agricultural soils with shallow root depths and forest with large root depths is seen in Table 3.

Table 3 Land-use types and root depth (m)

Land-use #	Name	root depth (m)
0	Water body	Large
1	Agriculture (mainly sugar cane)	0.5
2	Urban area	0.25
3	Tree plantations	3.0
4	Campo cerrado	1.5
5	Mata	2.5
6	Cerradão	4.0

Finally, the soil types have been classified. The complex soil maps of the area have been simplified, reducing the soil classes to 12. For each soil a table of soil physical parameters exists, specifying the infiltration rate, the hydraulic conductivity, the wilting point and field capacity and the porosity. The 12 classes correspond to the international texture soil classification.

This soil map has been linked to a table with texture classes that contains the hydraulic properties of the soils. In conclusion, the dominant soil type is a clayey soil with aggregates. In some places these clayey soils have developed into Terra Rossa. The second major soil is arenitic and has deep profiles with quartzitic sand. Hydromorphic soils occur along the river bed. The city is underlain by Chernosem with a clayey texture. The texture classes range from Gravel (0) to Clay (11) with the intermediate classes (Figure 5c).

Finally, based on the soil map and the geological map, the hydraulic conductivity of the sub-soil has been classified. The hydraulic conductivity of the subsoil was classified into general classes ranging from ‘very low’ to ‘very high’. Within the program an expert can assign real values. In this case the real values are given in mm/d as infiltration capacity. A subsoil conductivity of below 7.5 mm/d will – depending on the thickness of the soil cover – trigger interflow and reduce recharge. In general, a hydraulic conductivity of above 25 mm/d exceeds the daily percolation rates and does not create an accumulation and lateral drainage of water.

The generation of interflow is a complex process that dominates in areas with a pronounced morphology, steep slopes and a clear contrast between soil and sub-soil. Interflow becomes part of the runoff and reduces recharge. We believe that especially in hillslopes of the Serra Geral Frm. the contrast between fresh basalt and overlying soils can produce such intermediate runoff processes. The existence of interflow can be recognised from hydrographs as a second pulse with a delay of few days. The role of interflow in the study area Ribeirão Preto needs to be assessed based on further data.

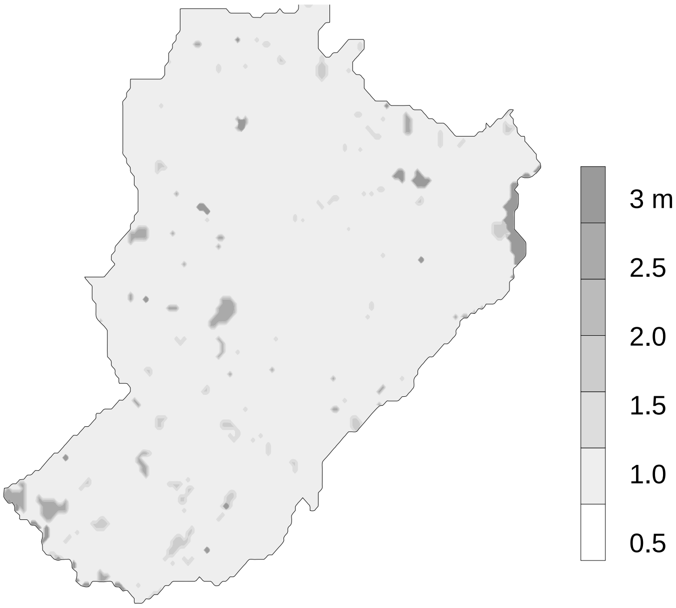


Figure 12 Classification of soil physical properties: thickness of the root-zone (m)

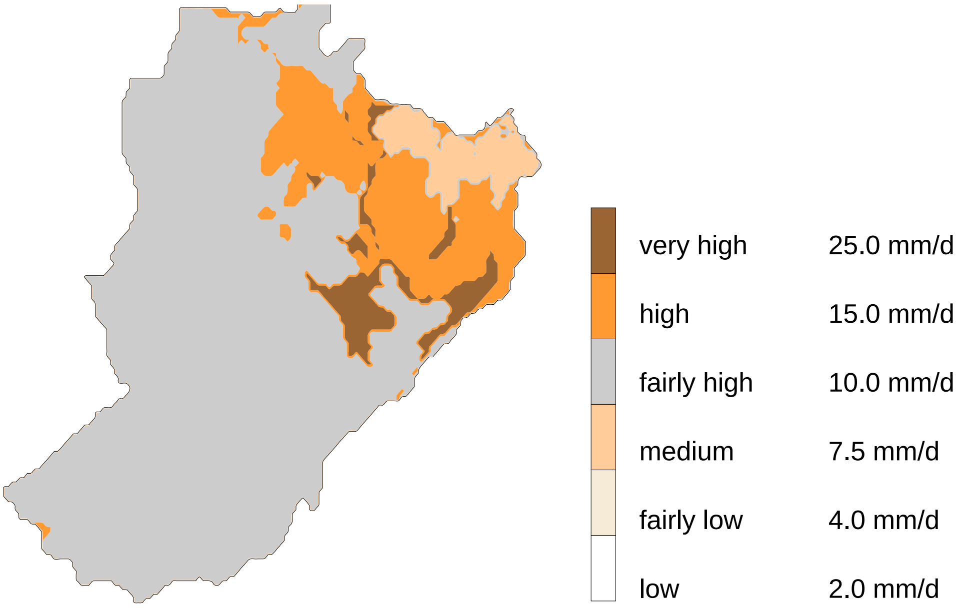


Figure 13 Classification of soil physical properties: hydraulic properties of the sub-soil. The values represent classes that are related to real values within a program table (see above)

5.3.3 Recharge Calculation

Based on the parameter maps and the input time series of meteorological parameters, different runs for the determination of recharge were made. The runs have been carried out for typical land-use / soil complexes and for the study area as a whole.

The total actual evaporation figures corresponded well with existing data (about 1050 mm/y). The different runs yielded direct recharge rates of 136 to 250 mm/y for soils of average thickness. The recharge timing could already be derived with first events starting in December and the major peak following in February to March.

The recharge calculation for an average soil type (Soil with clayey texture aggregated, class 5) with sugar cane as land use yielded the values shown in Table 4.

Table 4 Water Balance Model Run 1997 to 1999

Annual sum of water balance element		
Total Runoff	368	mm/y
Rain	1413	mm/y
Evaporation	1039	mm/y
Direct Runoff	236	mm/y
Recharge	**132**	**mm/y**
Storage Change	5	mm/y

A major part of the rainfall of 1413.27 mm/y evaporates and is used for transpiration. Due to the thick soils, quite impermeable texture and good storage properties, the recharge rates are quite low on average. Direct runoff amounts to 236 mm/y. The total runoff also includes indirect runoff components such as interflow that are generated within the soil profile due to low subsoil permeability. The total runoff amounts to 368 mm/y. The storage change is due to differences in soil moisture state between the beginning of the model run and the final state.

The average recharge rate is 132 mm/y. Locally recharge rates reach values of 250 mm/y. Higher recharge rates are observed were the soil texture is sandy and were land-use with shallow root depth prevails.

The recharge calculation has been carried out for the whole study area for the years 1997 and 1998. The calculation was based as described above on the input meteorological data and on the distributed parameter maps. The result is shown in Figure 14. Groundwater recharge is highest in the area covered by unconsolidated Cenozoic sands, and in the outcrop area of the Botocatu Frm. The recharge reaches more than 200 mm/y. Here, the higher permeability of the soil, the lower field capacity and the permeable subsoil favour higher groundwater recharge.

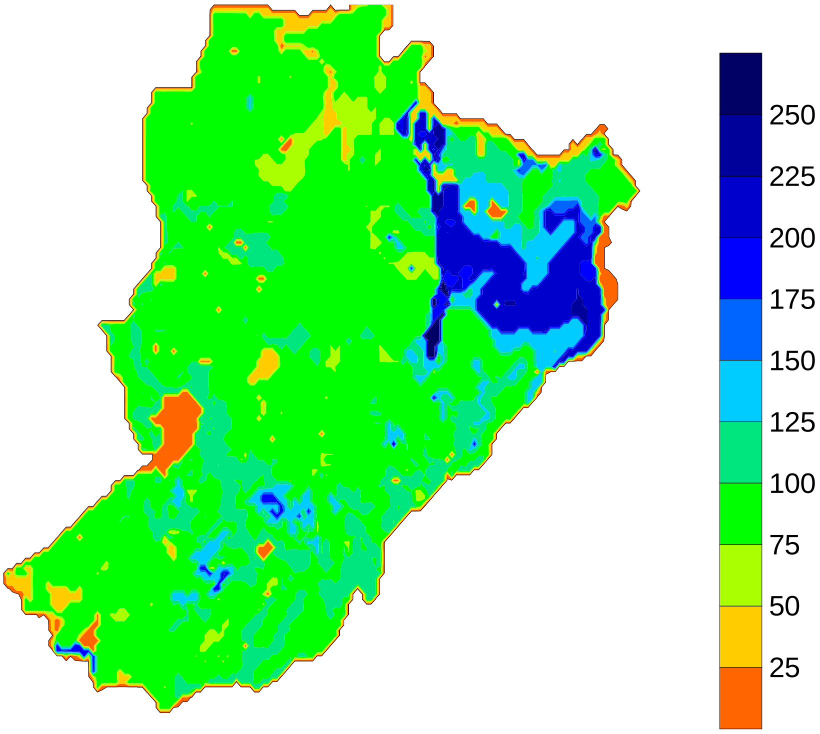


Figure 14 Recharge map of the study area (September 1996 to August 1997), recharge is given in mm/y

The remaining part of the study area is mainly covered by soils that have developed on the Serra Geral Frm. In these areas groundwater recharge ranges between 50 and 100 mm/y. Soils have a lower hydraulic conductivity because of their clayey texture caused by the weathering of the silicates in the basalt down to residual clay minerals. A variation within this area is caused by land-use differences and differences in the soil type. The city of Ribeirão Preto does not have clearly different recharge figures. This is not stated as a final result. The modelling of recharge from urban areas is based on special parameters that can not be derived from geology or soil cover maps. For urban areas specific information on the type of settlement and drainage is needed that was not available. Often cities have higher recharge rates due to the artificial recharge from network losses of the water supply system. Only hydrochemical and isotope investigations and subsequent mixing cell calculations or very detailed potentiometric maps can give further information on such processes.

The time variation of recharge is shown in Figure 15 (next page in a series of 12 maps). The sequence of maps was derived from a REGIS run, were recharge maps were printed on a monthly basis. The sequence from September 1996 to August 1997 shows clearly how the recharge is distributed in space and in time. These results confirm the remarks on the temporal distribution of recharge and allow to refine the description of recharge dynamics.

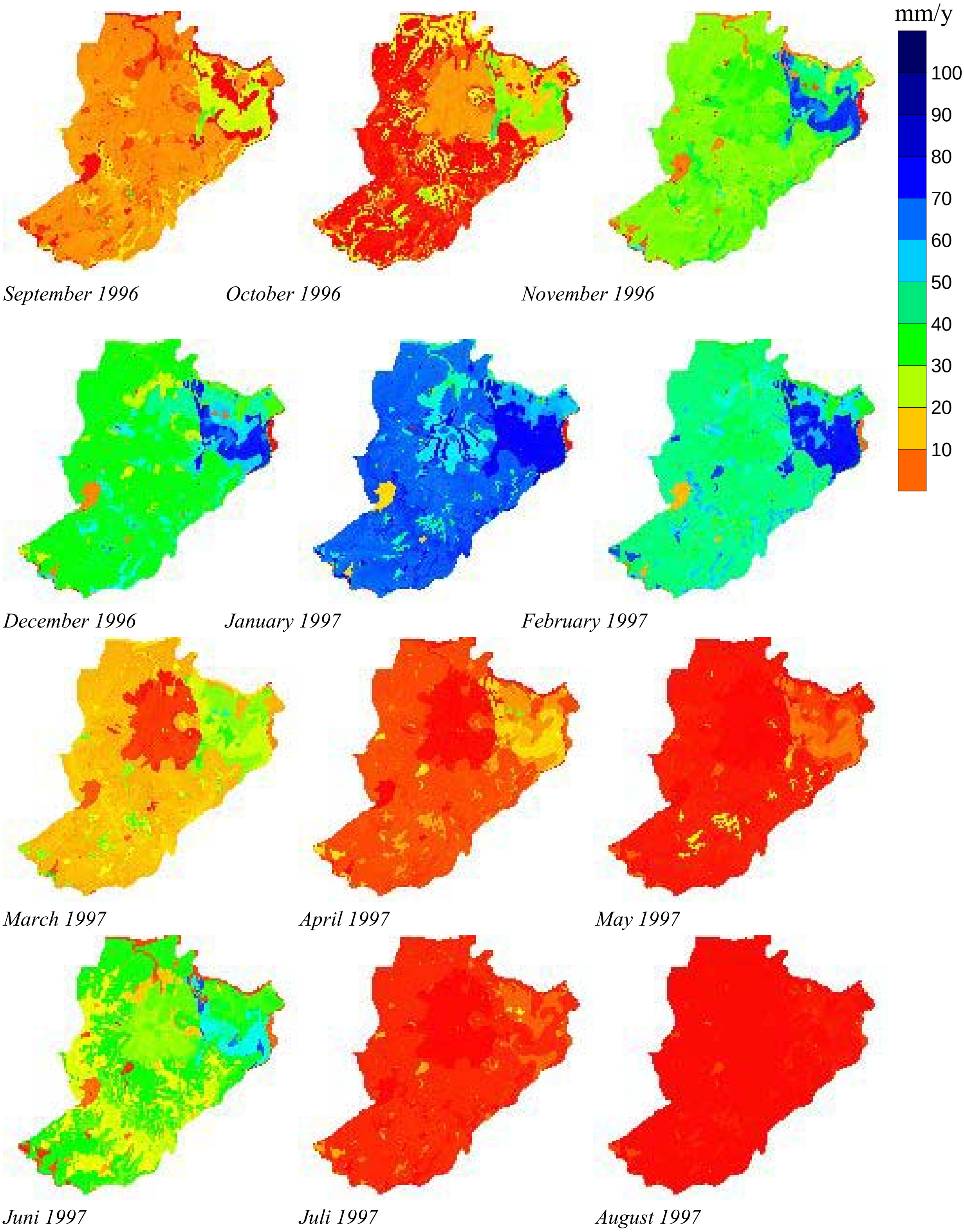


Figure 15 Monthly recharge maps of the study area for the year 1997 (September 1996 to August 1997)

The month with highest recharge was January 1997. However, in the permeable areas recharge takes place from November until March. Within the Serra Geral Formation recharge with lower intensities takes place from November until February. September, October and April through August have low recharge rates, in general. However, in the specific case of the season 1996/1997 a single month with some recharge was observed.

The recharge rates have been validated by Prof. Schuler, who used a groundwater model to delineate the groundwater protection zones. A groundwater model needs recharge rates as input parameter. If the other parameters – hydraulic conductivity, porosity, thickness of the aquifer – are estimated correctly and represent the aquifer well, the model will only run with recharge rates that correspond more or less to the natural conditions. A model fit was achieved with a rate of 60 mm/y for the Serra Geral Frm. and about 140 mm/y for the outcrop of the Botocatu Frm.

6 Conclusions

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. The soil has good storage properties, reducing the amount of fast percolation and providing water storage for evaporation. Recharge takes place mainly between December and February. Recharge ranges from about 200 to 250 mm/y in highly permeable areas, mainly outcrops of the 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. The recharge maps show the temporal distribution of recharge with highest rates in January, February. This is confirmed by the fact that the isotopic signature of the groundwater corresponds to the isotopic signature of rainfall of these months.

Since the water balance model is based on physical parameters the results are valid within the accuracy of the simplification of physical processes and parameters. However, these results require a validation with independent methods. The isotope investigations should be extended to ^{14}C studies along flow-paths in the Botocatu aquifer. The study of young groundwater should include or the Tritium / Helium method or other trace gases such as Sulfurhexafluoride or CFCs. It is very important to establish runoff measurements and water level – discharge relationships for the validation of results.

7 References

ARNOLD, J.G., R. SRINIVASIN, R.S. MUTTIAH, AND J. R. WILLIAMS. (1998). Large Area Hydrologic Modelling and Assessment: Part I. Model Development. JAWRA 34(1):73-89.

ARNOLD, J.G. AND ALLEN P.M. (1992) A Comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69.

BREDENKAMP D.B., BOTHA L.J., VAN TONDER G.J., VAN RENSBURG H.J. (1995) Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. Water Research Commission, Pretoria.

FACHSEKTION HYDROGEOLOGIE IN DER DEUTSCHEN GEOLOGISCHEN GESELLSCHAFT (1999): Hydrogeologische Modelle – Ein Leitfaden für Auftraggeber, Ingenieurbüros und Fachbehörden. In: Schriftenreihe der Deutschen Geologischen Gesellschaft, Hydrologische Beiträge, Heft 10, 36 p.

GALLO,G.,SINELLI,O.- 1980- Estudo Hidroquímico e Isotópico das Águas Subterrâneas na região de Ribeirão Preto,SP. Revista Brasileira de Geociências,v.10,p.129-140.

INTERNATIONAL ATOMIC ENERGY AGENCY (1996) Manual on mathematical models in isotope hydrogeology. IAEA TECDOC-910.

SIMMERS I. (1990) Estimation of Natural Groundwater Recharge. NATO ASI Series, Series C, Mathematical and Physical Sciences, Vol. 222, Reidel Publ.