Institute of Environment & Resources Technical University of Denmark

M.Sc. Thesis

Modelling Concepts for the Sustainable Management of the Sian Ka'an Biosphere Reserve, Quintana Roo, Mexico

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Cover photo: Sam Meacham

### Abstract

Urban, industrial and agricultural activities threaten the groundwater resource that feeds the Sian Ka'an Biosphere Reserve – a UNESCO World Heritage site on the Caribbean coast of the Yucatan Peninsula, Mexico. The area has a complex karstic geology with high permeability features, and the thesis investigates how the water resource dynamics of the catchment that encompasses the Reserve can best be modelled. A conduit-matrix model has been found to be appropriate for modelling groundwater flow in the catchment on a local scale, whereas an equivalent porous medium model is appropriate for regional scale modelling. High permeability zones have been identified based on visual inspection of satellite imagery and confirmed using frequency-domain geophysical measurements. These zones have been incorporated into the model scenarios and have been found to significantly impact the size of the catchment. The regional hydrological modelling has shown that a significant potential threat to the Reserve is posed by the nearby urban and agricultural areas of Felipe Carrillo Puerto and Andres Quintana Roo, from where pollutants may be able to reach the Reserve in less than 10 years. Also pollution from more distant areas may be able to reach the Reserve assuming high permeability in the identified structures. Moreover, it cannot be excluded that pollution from the area covered by the proposed development plan for Tulum can spread to the Reserve. The visual outcomes of the hydrological models is expected to be valuable inputs to decision making processes concerning the management of the groundwater resources of the Sian Ka'an catchment in the future.

## Preface

The present M.Sc. thesis in environmental engineering has been carried out from 13 March to 10 October 2006. The work is accredited 35 ECTS credits and has been carried out at the Institute of Environment & Resources, Technical University of Denmark.

The present project is the beginning of a larger research project with focus on the water management and hydrology of the area encompassing the Sian Ka'an Biosphere Reserve, a UNESCO World Heritage Site in the State of Quintana Roo, Mexico. Thus, the work initiated in this thesis will be continued and developed in the coming years through cooperation with different research institutions in Denmark, Europe and Mexico.

Kgs. Lyngby, Denmark, 10 October 2006

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A part of our work has included gathering of hydrological data for the location of our study. During this project we have therefore received a lot of different data, and we have not had the chance to use all of it in the present thesis. However, we would like to take this opportunity to thank all the people who have generously provided us with data, permission for line map use etc. As the project continues in the future we expect to be able to make good use of it and we would therefore like to thank Dr. Antonio Badan for tidal data, and the following cave explorers for line map permissions: A. Alvarez, N. Berni, B. Birnbach, J. Coke, K. Davidsson, F. Devos, P. Dotchon D. Jones, C. Le Maillot, D. Lins, A. Matten, S. Meacham, Z. Motycka, B. Philips, A. Pitkin, R. Power, S. Richards, R. Schmittner, D. Sieff, , and J. and R. Wiejski-Wolschendorf.

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## DVD Appendix Overview

The following table lists the data provided on the DVD-appendix.

The data for the ProTEM47 inversion is provided so the reader may look at all the models and also perform the inversion him/herself if required.

Documentation of the processing of water table data is provided in spreadsheets.

Model folders for the conduit-matrix model and the regional equivalent porous medium model (with model setup files and model result files) are given on the DVD-appendix so that the reader may study the results of the model runs further without having to set up the models him/herself. Water balances of the conduit-matrix models may be found in spreadsheets in the respective model folders.

File/Folder	Description
AD CHAPTER 4 – SALTWATER/FRESHWATER CONFIGURATION	
ProTEM47 data	Raw data files and corrected data files + spreadsheet with instrument specifications for each site. Note that the data have been named with the following convention: (site code name)(rep. frequency)(gain)(current).dat e.g. tulum0128511.dat. An 'n' in the data file name indicates that it is a noise measurement.
Tulum01 Tulum05 Tulum08	Each folder contains: - Raw data and *.geo-file and *.pff file used in the data treatment for each location. - TEMFiles folder with files for different tests made in the data treatment. - SavedModels folder with the files for the models mentioned in the main report. In the Tulum01/SavedModels folder: * Tulum01_noiz2 is the best found model, also described in the main report * Tulum01_UHlong is the model where a trial was made, where the last 10 gates of the UH segment were <i>not</i> trimmed * Tulum01_restrictSUP is the model made by constraining the resistivities of the 3 layers to the values found from geoelectric multielectrode measurements in the area by Supper et al. (submitted). The result was also presented in the main report. * Tulum01_restrictMRV is the model made by constraining the resistivities of the 3 layers to the values generally used by Mario Rebolledo Vievra
AD CHAPTER 5 – CONFIGURATION OF FRESHWATER HEADS	
Water table observation data.xls	Raw data of head observations from own field studies, INEGI, CAPA and CNA. The data has been processed to yield average values above mean sea level and also heads as predicted by the analytical solution have been calculated.
Water table calibrations - 1D model.xls	Calibration of analytical solution to the observed heads. There are 8 different calibrations; four for fixed recharge (15, 30, 45 and 60%) and four for fixed hydraulic

	conductivity (37500, 75000, 112500 and 150000 m/day) as found for the fit to the halocline	
Averaged water table data. xls	Observed freshwater heads averaged over a 10 km x 10 km grid with corresponding standard deviations. Also contains calibrations of the analytical solution to this data	
AD CHAPTER 7 – ANALYSIS OF STRUCTURES WITH GEOPHYSICAL METHODS		
EM34 measurements.xls	Coordinates and raw data from the EM34 measurements of Vigia Chico Road, Holbox Fracture zone and Caapechen transects, as well as data from Cristal, which showed the suitability of the EM34 method for detecting conduits, and data from Lirios, which show an anomaly in a brackish water environment at the beach (i.e. an anomaly with a <i>lower</i> value than the background value).	
em34.m R_H.m em34_40m.m R_H_40m.m em34_Manati R_H_Manati	Matlab input files for quickly calculating the result of the EM34 forward modelling. Input is entered into the em34.m- file in the following order: the apparent conducitivity of Layer 1, Layer 2, Layer 3, and the depth from the ground surface of Layer 2's top and Layer 3's top.	
AD CHAPTER 8 -	CONDUIT-MATRIX MODEL	
MOUSE_b (upstream head: 900 mm), MOUSE_c (upstream head: 400 mm), MOUSE_d (upstream head: 600 mm), MOUSE_e (upstream head: 2000 mm), MOUSE f (upstream head: 2500 mm)	MOUSE models used for determining upstream head in the conduit-matrix model and its corresponding discharge.	
SHEMOUSE_V	Conduit-matrix model with no recharge	
SHEMOUSE_W	Baseline conduit-matrix model	
SHEMOUSE_X	Conduit-matrix Head Increase Model	
SHEMOUSE_Y	Conduit-matrix Head Decrease Model	
SHEMOUSE_Z	Conduit-matrix K Increase Model	
SHEMOUSE_ZA	Conduit-matrix K Decrease Model	
SHEMOUSE_ZF	Conduit-matrix Inter-Conduit Spacing Increase Model 1	
SHEMOUSE_ZB	Conduit-matrix Inter-Conduit Spacing Increase Model 2	
SHEMOUSE_ZC	Conduit-matrix Inter-Conduit Spacing Decrease Model	
SHEMOUSE_ZI	Conduit-matrix Conveyance Increase Model	
SHEMOUSE_ZJ	Conduit-matrix Conveyance Decrease Model	
SHEMOUSE_ZD	Conduit-matrix Recharge Decrease Model 1	
SHEMOUSE_ZE	Conduit-matrix Recharge Decrease Model 2	
SHEMOUSE_ZG	Conduit-matrix Deeper Lower Level Model	
SHEMOUSE_ZH	Conduit-matrix Shallower Lower Level Model	
SHEMOUSE_halocline_1	Conduit-matrix model with a lower level similar to the slope of the halocline	
SHE_A	3-layer equivalent porous medium model, steady-state	
SHE_B	1-layer equivalent porous medium model, steady-state	
SHE_A_transient	3-layer equivalent porous medium model, transient	
SHE_B_transient	1-layer equivalent porous medium model, transient	
SHE_C	Block equivalent porous medium model (no high-permeable zone), steady-state	
SHE_C_transient	Block equivalent porous medium model (no high-permeable zone), transient	

AD CHAPTER 9 – REGIONAL-SCALE HYDROLOGICAL MODEL

Each folder contains a spread sheet with the results for the different runs of the scenario. There are MIKE SHE model files for the run with the best fit. The last number in the name of the MIKE SHE files correspond to the run

number also found in the spread sheet. R30 or R60 in the file name indicates the amount of recharge used for that model. PT or PTrack in the folder name shows where results from particle trackings can be found. WELL in the filename indicates the experiment with inserting wells to simulate increased evapotranspiration. The results of the calibrations are summarized in Appendix Q in the Appendix Report.

01 SZ 1	Contains: *Steady state model including only flow in the saturated
	zone, with uniform hydraulic conductivity
	*Steady state model with overland flow (OL)
01.07.0	*Particle tracking for the model with overland flow
01 SZ 2	Steady state model including only flow in the saturated zone, with two zones of different hydraulic conductivity
01 SZ 2	Steady state model including only flow in the saturated
	zone, with three zones of different hydraulic conductivity
02 SZ+HPZ	Steady state model including flow in the saturated zone and
	high permeability zones (structures)
03 SZ+LPZcoast	Steady state model including flow in the saturated zone and
	a low permeability zone along the entire coast
04 SZ+HPZ+LPZcoast	Steady state model including flow in the saturated zone,
	high permeability zones (structures) and a low permeability
	zone along the entire coast
05 SZ+LPZtulum	Steady state model including flow in the saturated zone and
	a low permeability zone along the coast between the
	northern boarder of Sian Ka'an and the northern border of
	the model area
06 SZ+HPZ+LPZtulum	Contains:
	*Steady state model including flow in the saturated zone,
	high permeability zones and a low permeability zone along
	the coast between the northern boarder of Sian Ka'an and
	the northern border of the model area
	*Steady state model with overland flow (OL)
	*Particle tracking for the model with overland flow as well
	as with wells to simulate effect of increased
	evapotranspiration.
07 SZ+Holbox	Steady state model including flow in the saturated zone,
	high permeability zones (structures) and a continuation of
	the Holbox fracture that connects it to the other structures
08 SZ+Perryfault	Steady state model including flow in the saturated zone,
	high permeability zones (structures) and the fault identified
	by Perry <i>et al.,</i> 2002)
09 SZ+RioHondofault	Steady state model including flow in the saturated zone,
	high permeability zones (structures) and the extended Rio
	Hondo fault zone
10 SZ+HolPerRio	Contains:
	*Steady state model including flow in the saturated zone,
	high permeability zones (structures) and the three fault
	zones included in scenario 07, 08 and 09.
	*Steady state model with overland flow (OL)
	*Particle tracking for the model with overland flow

## 1 Introduction

### 1.1 Background and Motivation

The Sian Ka'an Biosphere Reserve is located on the eastern coast of the Yucatan Peninsula in the state of Quintana Roo, Mexico. This 5280 km<sup>2</sup> large nature reserve comprises rainforests, wetlands and coral reefs with a rich biodiversity including also endemic and endangered species, and is listed as a UNESCO World Heritage site (UNEP WCMC, 2001; UNESCO, 2006). The wetlands of the reserve are entirely fed by groundwater and constitute one third of the total reserve. The groundwater of the region partly flows via underground caves, which themselves are home to various cave-adapted fauna, such as crustaceans and fish, and the caves have an important recreational and cultural value for the area.

However, the freshwater aquifer which provides water to these systems is vulnerable, as it is a thin freshwater lens floating on top of saline water in a karstic limestone medium. The karstic nature means that water flows in the matrix, in fractures as well as in the underground caves, and it is thus a complex system. Soil cover is limited, which together with the rapid flow velocities in the karst results in a limited capacity for retention of contaminants (Prohic, 1989, cited in Escolero *et al.*, 2002).

The thin freshwater lens is the main source of freshwater in the area, since surface water bodies are scarce. Yet, the water resources of the area are threatened from various sides. An expanding tourism industry is currently encroaching southwards towards the Sian Ka'an area, and this is followed by an increase in water demand and an increased wastewater production. Tourism is one of the most important sources of income in the area (Battlori *et al.*, 2000) and in February 2006, a development plan for the town of Tulum, located just north of Sian Ka'an in an area with known extensive underground cave development, was presented. The plan is currently under revision, following substantial resistance from the local community and various organizations, but the latest proposal from the municipality (June 2006) suggests development from the existing ~1,200 hotel rooms (in 2003) to 11,000 rooms in 2025. This is expected to increase the population numbers in the area from ~12,000 people in 2003 to 120,500 inhabitants in 2025 (Solidaridad, 2006a; Solidaridad, 2006b; PDU, 2006), thus suggesting a significant development. However, the plan does not take hydrological flow aspects into account, nor does it quantify the available water resources or consider disposal of wastewater (PDU, 2006).

In addition, domestic, agricultural and industrial pollution pose a threat to the groundwater resources, e.g from the larger town of Felipe Carrillo Puerto directly west of the Sian Ka'an Biosphere Reserve, with about 18,000 inhabitants in 2000 (FCP, 2006), and from the agricultural areas in the southern and western parts of Quintana Roo (UNEP WCMC, 2001). Pollution of the aquifer is critical, since it is hardly possible to remediate a karstic aquifer (Escolero *et al.*, 2002).

In reality, the magnitude of the groundwater resource is not known, since the amount of recharge the aquifer receives is not well determined, and since the thickness of the freshwater lens in Quintana Roo has not been studied on a regional scale, but only by few point measurements scattered over the area. Therefore, there is a need for further studies of the area's groundwater resource, both to protect the internationally important nature reserve of Sian Ka'an, and to ensure that the groundwater resource can supply the inhabitants with water also in the future. In addition, it is important to study the flow patterns of the groundwater, so that the contamination flow patterns of any pollution can be established, and so

groundwater protection zones can be delineated. Studies of the groundwater flow is also important in order to determine pollution travelling times, as a step in evaluating the vulnerability to pollution of the recipient, which may be the wetlands of Sian Ka'an or the coral reefs along the coast. Ultimately, having this knowledge will also be important for the tourism industry itself, in order to prevent the degradation of the exact same resources that the visitors come to enjoy, namely the nature, the sea, the reef and the cave systems, and for the inhabitants which depend on the groundwater resources. The need for the protection of the water resources of the area and for further research on the area's hydrological system was also expressed by local stakeholders, governmental and non-governmental institutions on a workshop in 2003 (ASK, 2003b).

Hydrological models are important tools for investigations of aquifers and for groundwater management. Hydrological modelling in karst areas is, however, a developing field, and is complicated due to the extremely heterogeneous nature of the geologic medium, as well as the combination of both diffuse flow and flow through the conduits and fractures. (Pinault *et al.*, 2004; Atkinson, 1977). Especially hydrological modelling of coastal karstic aquifers has in general been limited (Arfib & de Marsily, 2004). Nevertheless, modelling and increased understanding of karstic aquifers is important, also on a global scale, as approximately 25% of the world's population depend on groundwater from karstic aquifers to a large extent (Ford & Williams, 1989).

### 1.2 Problem Statement

In the light of the points mentioned above, the goal of the thesis project is to investigate the hydrological system in and near the Sian Ka'an Biosphere Reserve. The main objective of the thesis project is to answer the following question:

"In which ways can the water resource dynamics and flow patterns in the catchment that includes the Sian Ka'an Biosphere Reserve be modelled, and how can a hydrological model be used to aid the protection of the wetland water resources from contamination?"

The work is thus a first step in understanding the groundwater flow patterns of the area and requires the following activities:

- Determine the current level of knowledge of the hydrologic system and develop a database with available data, not only to be used in this thesis but also in further projects.
- Investigate the state of the aquifer, since it consists of both saltwater and freshwater. It is necessary to investigate the controls on the position of the saltwater/freshwater interface and the controls on the position of the freshwater table, i.e. the lower boundary and the upper boundaries of the freshwater lens.
- Investigate the structure of the aquifer, since it is a karst medium, and structures such as faults, fractures and underground cave conduits may have significant impact on the direction of groundwater flow and its travel time, as well as on the extent of the catchment comprising the Sian Ka'an Biosphere Reserve.
- Conduct numerical modelling of the aquifer state based on the aquifer structure, and with this tool explore how the aquifer can best be represented by a hydrological model, investigate the

flow patterns in the area and factors that have a significant impact on the groundwater flow. With the model also examine travel times and catchment zones.

### 1.3 Approach

In January and February 2006, a pre-thesis was carried out in preparation for the thesis work (Neuman & Rahbek, 2006). Through literature study and the setup of a first regional-scale hydrological model it was established what data would be needed in the thesis work and how they could be obtained.

A field trip to the study area in Quintana Roo was subsequently carried out during 6 weeks from March to May 2006. The purpose of the field trip was to obtain the data needed for the further thesis work as well as to acquire a better knowledge of the area of study in general. Information was obtained through visits to Mexican water institutions, through cooperating partners as well as through interviews with key persons. Moreover, the following field work was carried out:

- Geophysical measurements with time-domain electromagnetic (TEM) equipment to determine the depth to the saltwater/freshwater interface along a profile perpendicular to the coast.
- Geophysical measurements with frequency-domain electromagnetic (FEM) equipment over structures identified on satellite imagery to investigate whether the structures can be related to zones of higher permeability in the ground.
- Measurements of groundwater levels in wells throughout the main part of the model area with a water level indicator.

The following approach has been used for the during the thesis work:

- Study and processing of data and information obtained during the field trip.
- Analysis of the depth of the lower level of the freshwater lens, based on the TEM data and data from the literature. This includes 1D modelling of the data with an analytical model.
- Analysis of water table, including 1D modelling of freshwater heads with an analytical model.
- Analysis of satellite imagery to identify possible regional aquifer structures.
- Analysis and forward modelling of the obtained FEM data.
- Development of a simple conduit-matrix hydrological model, using a combination of the MIKE SHE and the MOUSE modelling codes (DHI, 2006), sensitivity analysis of the model and analysis of its applicability for modelling the aquifer on a local and regional scale.
- Development of a regional-scale equivalent porous medium hydrological model using the MIKE SHE modelling code. Analysis of various aquifer structure scenarios with this model, as well as analysis of catchment zones and travel times.

### 1.4 Structure of the Report

In line with the general approach presented above, the present report is structured as follows:

In Chapter 2 the background on the model area is presented. A general background for the geophysical methods is given in Chapter 3 to provide a basis for understanding the results of the geophysical measurements. Other theory, e.g. on numerical hydrological modelling, as well as details on TEM or FEM methods, is presented in the relevant chapters where it is used.

Chapters 4 and 5 provide an analysis of the <u>aquifer state</u>, encompassing first a chapter on the configuration of the halocline, i.e. the interface between the freshwater lens and the underlying saltwater, to define the *lower extent* of the freshwater resource, and second, a chapter on the configuration of the freshwater heads in the model area, thus defining the *upper extent* of the freshwater lens.

The <u>aquifer structure</u> is analyzed in Chapters 6 and 7 and comprises a chapter on *identification* of the structures with satellite imagery, and a chapter which uses the electromagnetic measurements to investigate if the presence of high-permeability zones under the structures can be *confirmed*.

<u>Numerical modelling</u> based on aquifer state and aquifer structure is undertaken in Chapters 8 and 9. This also includes an evaluation of the possible ways of representing the aquifer on local and regional scales. In different scenarios the catchment of the Sian Ka'an Biosphere Reserve is analyzed along with an investigation of travelling times from potential sources of pollution.

The final chapters discuss and present possible management perspectives in relation to the results from this thesis, and conclude on the findings. Finally, directions for future research are given.

## 2 Description of Model Area

The Yucatan Peninsula is located in south-eastern Mexico between latitudes 17.49 and 21.37 degrees N and longitudes 86.42 E and 92.28 W and borders the Gulf of Mexico to the west and the Caribbean Sea with the Mesoamerican Reef to the east. It comprises the Mexican regional states of Yucatan, Quintana Roo and Campeche, the northern part of Belize, and Guatemala's northern territory of El Petén. Figure 2.1 shows a map of the Yucatan Peninsula, including the Sain Ka'an Biosphere Reserve and various cities, which will be mentioned during the report. The name 'Rivera Maya' used in the report describes the Caribbean coastal stretch from Xcaret to Tulum while 'Costa Maya' is the coast from south of Sian Ka'an to Xcalak.

This chapter first describes the delineation of the model area. Then the conditions of the model area are described.

### 2.1 Delineation of the Model Area

#### 2.1.1 Initial Delineation

In the pre-thesis the initial model area (i.e. the area believed to contribute with water to the Sian Ka'an Biosphere Reserve) was delineated based on topography since knowledge of direction of groundwater flows on the Yucatan Peninsula is very limited. Visual inspection of a topographic map derived from the Shuttle Radar Topography Mission (SRTM) of the National Aeronautics and Space Administration (NASA) and National Geospatial-Intelligence Agency (NGA) (USGS, 2004) was used for the purpose.

The model area is delineated to the east by the Caribbean Sea and to the west by topographical divides under the assumption that that groundwater divides coincide with topographic divides. This assumption is not necessarily valid since underground conduits may change the location of the groundwater divide. However, the locations and direction of subsurface conduits are presently not known, and the approach presented here is considered the most adequate working approach which can currently be applied.

North of the Sian Ka'an Biosphere Reserve the initial model area was defined by using dividing streamlines to determine the location of the boundary that intersects the coast. Underground conduits in this area discharge into the ocean in a north-western/south-eastern direction, and it is therefore assumed that the groundwater flow and hence the model area boundary is roughly parallel to these features. However, when using this principle it is necessary to have the boundary relatively far from any sources or sinks, e.g. wells and cenotes, as well as relatively far from the area of interest, i.e. the Sian Ka'an Biosphere Reserve. Therefore, the northern model boundary which transects the coast was placed just north of the town of Tulum.

The Belize border was chosen as the southern boundary point to intersect the coastline. The resulting initial model area is displayed in Figure 2.2 indicated by a grey line.



Figure 2.1. Map of the Yucatan Peninsula. From Frommers (2006).

#### 2.1.2 Modified Deliniation

Water level data and literature collected during the field trip has indicated that the initial model area comprises areas that do not contribute with water to the Sian Ka'an Biosphere Reserve.

Water level data from INEGI (no year), have shown that the general trend of the water table being located < 25 m above mean sea level in the entire model area, is disturbed by observations from the interior, hilly part of the Peninsula, where water tables are > 100 m above mean sea level<sup>1</sup>. This may indicate that the area where the high water levels are observed could correspond to an area with perched groundwater bodies and that the area is therefore not a part of the catchment that contributes with water to the Sian Ka'an Biosphere Reserve. Whether lower lying groundwater beneath the perched water bodies in this area may actually reach the Reserve is not known, but based on the previous it has been decided to omit the area from the model area, as shown in Figure 2.2 and Figure 2.3 (larger circle).



**Figure 2.2**. Model area as defined in the pre-thesis (grey line) delineated based on visual inspection of the SRTM topographic map. The new model area (red line) modified based on information on flow divides. The Sian Ka'an Biosphere Reserve is also indicated (green line). The legend unit is meters above mean sea level (m.a.m.s.l).

<sup>&</sup>lt;sup>1</sup> It has been considered whether the high water levels is due to the hilly topography in this area, i.e. if very localized changes in elevation has caused errors in the calculated water levels relative to mean sea level. Running a 3x3 pixel averaging filter on the SRTM topographic map has ruled out that this is the case.

In addition, a study on the geochemical properties of the groundwater on the Yucatan Peninsula indicated that the Lakes Chichankanab and Esmeralda are located on a groundwater divide and the groundwater in the area west of these lakes is believed to drain into the Sierrita de Ticul fault (Perry *et al.*, 2002). Therefore, this area has also been omitted from the model area, as shown on Figure 2.3 (small circle).



**Figure 2.3**. The old (grey) and the new (red) model outline with a close-up of the modified area. The small circle encompasses the area west of Lake Chichankanab and Lake Esmeralda, where groundwater is believed to drain into the Sierrita de Ticul fault, whereas the large circle represents an area with what is assumed to be perched groundwater bodies. Legend unit is m.a.m.s.l.

The resulting model area is roughly 35,000 km<sup>2</sup> and spans approximately from the UTM coordinates x = 204000 in the west to x = 463000 in the east, and from y = 2275000 in the north to y = 1992000 in the south (in the UTM zone 16 North, WGS84 datum and ellipsoid). Most of the model area is situated in the state of Quintana Roo, and encompasses the municipality of Felipe Carrillo Puerto, as well as the larger part of the municipalites Ortón P. Blanco in the south and José María Morelos in the west and a smaller part of the municipality of Solidaridad to the north. In addition, the model area extends slightly into the state of Campeche (INEGI, 2006a). However, given that the majority of the model area is in Quintana Roo, most of the general information given below is focused on the conditions of this state.

### 2.2 Description of the Model Area

#### 2.2.1 Geology

The Yucatan Peninsula is the surface part of a 300,000 km<sup>2</sup> large limestone platform, depicted in Figure 2.4. The surface limestone formations originate from the Eocene up until the Holocene and were deposited in a sequence which reflects the gradual deposition on the sides of the emerging peninsula landmass (Butterlin & Bonet, 1960, 1962, Mejorda & Ramos, 1968, Lopez Ramos 1973, 1975, all cited in Ward, no year; Weidie, 1985, cited in Beddows, 2004). Thus, the eldest surface formations are found in the southern interior part of the Peninsula, while the limestones are younger closer to the present coast. This is seen in the simplified map of the geology also shown in Figure 2.4.



**Figure 2.4**. The Yucatan Platform, and the overall geological surface units of the Yucatan Peninsula. Modified from French & Schenck (1997), Weidie (1985, shown in Beddows, 2004), and Villasuso & Ramos (2000). Red line indicates the model area.

As seen from Figure 2.4, our model area consists of Paleo-Eocene deposits in the south-western corner (Icaiché Formation (Fm)), as well as Oligocene/Eocene limestones (Chichén Itzá Fm, and undifferentiated). The largest part of the model area is limestones of Miocene-Pliocene age (Carrillo Puerto Fm, Estero Franco Fm., Bacalar Fm). In a belt from the coast around Tulum and north of here, and roughly 5-10 km inland, Pleistocene limestones are deposited (Lauderdale *et al.*, 1979, cited in Ward, no year). These accumulated in only a few thousand years during a short-lived sea level high stand (<10,000 years) (Harmon *et al.*, 1983, cited in Ward, no year) on reefs on the platform margin and on back-reef platforms. The Pleistocene geology has a metastable mineralogy and are described as porous and permeable, and highly susceptible to dissolution by groundwater in seawater/freshwater mixing-zones (Ward & Brady, 1979; Ward, no year). In addition, Holocene deposits can be found in the Sian Ka'an area. Deposition of sediments is ongoing in e.g. lagoons, lakes and shallow coastal waters, and coral reefs are actively forming outside the Caribbean Coast. However, currents are strong outside the Caribbean coast, thus limiting carbonate deposition here (Beddows, 2004).

65 million years ago a great meteor hit the Yucatan platform and formed a crater now known as the Chicxulub impact structure located in the Yucatan State (Ebbing *et al.*, 2001). In geological boreholes from various locations in the Yucatan State several hundred meter thick layers of ejecta<sup>2</sup> have been encountered between Cretaceous and Tertiary sediments (Ward *et al.*, 1995, cited in Beddows, 2004; Urrutia-Fucugauchi *et al.*, 1996, Rebolledo-Vieyra *et al.*, 2000, Ward, Mihai Lefticariu & Perry, unpublished, all three cited in Perry *et al.*, 2002). However, Schönian *et al.* (2005) have recently shown that the ejecta blanket is far more widespread over the peninsula. Schönian *et al.* (2005) found significant deposits of ejecta in the area around Chetumal and about 50 km inland from here and showed that ejecta is commonly found at the surface in the southern part of Quintana Roo, on top of Cretaceous sediments. Only at the village of Bacalar the found ejecta lies below Neogene deposits (Schönian *et al.*, 2005). The ejecta layer has been found not to be a continuous blanket, most likely due to erosion of part of the ejecta blanket during the course of time (Schönian *et al.*, 2005; Shaw, pers. comm., 2006).

The ejecta present at the surface in southern Quintana Roo might explain the occurrence of a significant number of lakes and intermittently flooded and flooded areas in the inland areas. Such water bodies are not found in abundance elsewhere on the peninsula due to the high permeability of the limestone. However, the ejecta obtains a very low permeability when it gets wet (Shaw, pers. comm., 2006) and may therefore explain the existence of the swamps and perched inland water bodies here. In addition, Perry *et al.* (2002) documented that water sampled from boreholes and cenotes in southern Quintana Roo, and hence the southern part of our model area, has significantly elevated levels of  $SO_4^{2-}$ . This could indicate that the water in this area flows through evaporites present in the older sediments of this region and/or flows through ejecta layers, since ejecta is rich in sulphate (Perry *et al.*, 2002).

In the southern inland areas geological maps from INEGI (no year) also show the localized/spotted presence of other types of sediments than the Tertiary limestone (see Figure 2.5). On the INEGI maps these are denoted as "Quaternary" sediments, but they correspond well with areas where intermittent swamps or inland lakes are known to occur (cp. geology map with e.g. INEGI's map of areas subject to inundation, shown in Figure 2.19 in the Surface Water section of this chapter, or with ITMB, 2005). Thus, this fact as well as the recent findings by Schönian *et al.* (2005) makes it possible that the spotty "Quaternary" geological units inland on the INEGI maps are instead ejecta deposits.

<sup>&</sup>lt;sup>2</sup> or "impact breccia", i.e. debris ejected at the formation of the impact crater.



**Figure 2.5.** Geological surface layers according to INEGI (no year). For the areas where detailed INEGI maps have not been obtained the geology is the same as displayed in Figure 2.4. Colour coding follows the codes in Figure 2.4, except that the orange colour on the northern part of the Caribbean Coast indicates Pliocene formations according to INEGI's maps, but we believe this must be a mistake and instead this area represents Pleistocene sediments, since that would be in accordance with the literature. As seen, there are several smaller "Quarternary" units inland on these INEGI maps compared to the simple map shown in Figure 2.4.

Soil layers above the limestones of the area may be very thin or completely absent, because limestones may generally dissolve without leaving residues, and no other geological materials are present which may produce clays or sand by weathering. The soil types present are mainly very permeable rendzinas and lithosols (Escolero *et al.*, 2002; Battlori *et al.*, 2000). In the northern part of the Yucatan Peninsula, soils are mostly only a few centimetres thick (Doehring & Butler, 1974), and generally on the peninsula as a whole the soil cover is rarely more than 20 cm deep.

The carbonate rocks of the underground in the model area are characterized by a large degree of fracturing as well as a large amount of dissolution features, such as conduits and caves, of varying sizes. In the pre-thesis the processes that create such karstic features were explained further. These dissolution processes makes the geology of the area a dynamic system, and are believed to have been ongoing for the past 125000 years (Steinich & Marín, 1997). The sediments of the model area have been characterized as being in the young and early mature stages of karstic erosion (Velázques Aguirre, 1986, cited in

Villasuso & Ramos, 2000). The limited soil cover and thus rapid and large infiltration only contributes to the rather rapid development of the dissolution features (Back & Hanshaw, 1970). However, within the time perspective of this project, the heterogeneities can be assumed to be static.

#### 2.2.2 Physiography and Topography

As displayed in Figure 2.6 there are 3 main fault systems on the Yucatan Peninsula, namely the Holbox Fracture zone, the Rio Hondo faults and the Sierrita de Ticul fault. In addition, the Chemax/Catoche fault zone is located just north of the Yucatan Peninsula (Shaub, 1983, cited in Ward, no year) (indicated with dotted line on Figure 2.6), but will not be treated here since it is not relevant for our area of study.

The Holbox fracture zone stretches north-northeast south-southwest from the northern part of the peninsula near Holbox Island, and is thus roughly parallel to the east coast of the peninsula. Currently, the Holbox Fracture zone is defined to end near Tulum (Southworth, 1985, cited in Beddows, 2004), thus having a length of 100-130 km, but it is possible that the system may intersect with the fault system of Rio Hondo (Southworth, 1985, cited in Beddows, 2004). A possible indication of this is the lakes south of Tulum, e.g. Lake Kan-Luum, Lake Chumkopo and Lake Chunyaxche that are aligned with the Holbox structures. The Holbox fracture zone is actually a series of elongated linear depressions, rather than faults. Chains of cenotes follow these features and wetlands form in some of these depressions (Perry *et al.*, 2002; Fedick *et al.*, 2000). Tulaczyk (1993, cited in Beddows, 2004) has suggested that the Holbox fracture zone depressions are a surface manifestation of underlying high permeability zones, thus having an important impact on underground water flow. Water is known to flow northward out of this zone but is likely also to flow southward as well (Marín, 2003, cited in ASK, 2003b). The location of a water divide in this zone has however not yet been identified, and any possible flow has not been quantified.

The Rio Hondo faults are a series of parallel normal faults trending northeast-southwest, and bounding a series of horsts and grabens, which are noticeable at the surface as a series of elongated water bodies, such as Lake Bacalar. They may be the prime control of the trend of the Caribbean coast, and of Cozumel Island, which is believed to be a horst between two faults (Ward, no year). However, on a topographic map these faults are only visible in the area around Chetumal and Lake Bacalar (SRTM, USGS, 2004).



**Figure 2.6**. Rough sketch of the location of main fault systems on the Yucatan Peninsula. The shown fault lines indicate the area, but not the exact number of faults nor their density and precise position. The Chemax/Catoche faults are only displayed as dotted lines since they will not be presented in detail in the text). After Weidie (1985, shown in Beddows, 2004). The fault suggested by Perry *et al.* (2002), and discussed in the text is indicated with a dashed line on the figure.

The Sierrita de Ticul fault is an important physiographic structure for the Yucatan Peninsula, located just outside our model area. It is an escarpment about 160 km long running northwest to southeast, and terminating inland at Lake Chichancanab. Shaw (no year) suggests that possibly it may continue underground further eastward, based on observed abrupt changes in depressions and lakes following the trend of the fault. However, with the information we have had at our disposal it was not possible for us to confirm this.

The Holbox fracture zone and the Rio Hondo faults are believed to have formed in the Eocene age, while the Sierrita de Ticul fault is probably of Mio-Pliocene age (Butterlin & Bonet, 1960, cited in CNA, 2001). Since then, little tectonic events are believed to have taken place, due to the sub-horizontal layering of the sediments (CNA, 2001).

The three main fault and fracture zones are also clearly seen from the topographical relief, as shown in Figure 2.7 and Figure 2.8.



**Figure 2.7**. The Holbox fracture zone and the Sierrita de Ticul fault zone are seen in the topography. Here displayed on the topographical map from the Shuttle Radar Topography Mission (SRTM) (USGS, 2004), which has been enhanced using the "Hillshade" function in the ArcGIS software with illumination from northwest and light source altitude 45°. In addition, the image has been stretched with histogram equalization using the ILWIS software in order to enhance the contrasts of the image.



Maps published by INEGI (no year) in addition indicate various fractures. These will be presented in Chapter 6. However, the main structural axis in the model area is northeast-southwest, just like the axis of the Holbox and Rio Hondo fault zones.

Finally, based on geochemical investigations, Perry *et al.* (2002) suggest a fault in the direction northnorthwest south-southeast from Lake Chichancanab at the inland end of the Sierrita de Ticul fault and down towards Cenote Azul located at Lake Bacalar near Chetumal (indicated with a dashed line on Figure 2.6). Lake Chichancanab is itself located at the foot of an escarpment (Shaw, no year).

Generally, the elevations of the Yucatan Peninsula and the model area are low, only up to maximum 396 m above mean sea level (SRTM map, USGS, 2004). The highest elevations are found in the southern inland part of the peninsula and decrease towards the coast.

East and west of the suggested fault of Perry *et al.* (2002), there is a noticeable difference in topography, as illustrated in Figure 2.9. West of the suggested fault, elevations are generally higher than 50 m.a.m.s.l. and the terrain is hilly, knobbed at places, with valleys as well as completely flat karst plains, reflecting an older heavily karstified surface. Where the ejecta depositions are present they contribute to a generally smoothly undulating relief (Schönian *et al.*, 2005). East of Perry *et al.* (2002)'s proposed fault, elevations range from zero to 50 m, with fewer undulations. Depressions and lakes in this area close to the proposed fault may display bends, perhaps due to folding associated with the formation of the Rio Hondo faults (Shaw, pers. comm., 2006). At the Rio Hondo faults themselves folds are obviously present, however elsewhere in the model area where it has been investigated, geological layers do not indicate folding (CNA, 2001).

As seen in some of the mentioned features above, e.g. the solution corridors of the Holbox fracture zone, dissolution of the limestone geology has played an important role in the physiography and topography of the model area,. Dissolution of limestone has also shaped bays at the coast (Shaw, 2003). In addition, cenotes are an important physiographic feature of the region. Cenotes are sinkholes, in which groundwater can be observed, because they intersect the groundwater table. They are formed by dissolution of underground limestone and collapse of the overlying surface limestone. They are abundant in the northern part of the Peninsula in general, and in the northern half of the model area. In the south, cenotes are rarely found (Schönian *et al.*, 2005). Cenotes may be connected underground by caves, but this is far from always the case. Nevertheless, underground dissolution features as well as fractures and faults may significantly impact the groundwater flow. Faults in the area are observed to transport significant amounts of water, as discussed by Shaw (2003), and Perry *et al.* (2002). Structures and caves will be treated in further detail in the "Caves" subsection of this chapter and in Chapter 6.



#### 2.2.3 Climate

The climate on the Yucatan Peninsula generally falls within the class Aw in the Köppen classification scheme, indicating hot tropical subhumid climate with a mean annual temperature over 22°C and an annual precipitation between 700 and 1500 mm. This climate has distinct wet/dry periods due to the migration of the intertropical convergence zone (Garcia, 1973, cited in May *et al.*, 1996; Beddows, 2004).

The rainy season coincides with the summer season, which extends from May to October, but the rainy season is brief and there is typically a dry spell in the middle of the summer (Alcocer *et al.*, 1998; Garcia, 1989 and Duch, 1988, both cited in Batllori *et al.*, 2000). Winter rainfall does also occur, and especially along the coastline of Quintana Roo a great part of the precipitation falls during the winter months (Duch, 1988, cited in Batllori *et al.*, 2000).

The annual average regional distribution of precipitation over the Yucatan Peninsula is displayed in Figure 2.10 and it is seen that the highest precipitation rates in the model area are expected along the coast and in the southern highlands, whereas the northwestern areas are the driest.



**Figure 2.10**. Isohyetal map from Villasuso & Ramos (2000), displaying spatial variation in the average annual precipitation on the Yucatan Peninsula. Unit is mm/year. The source of the data which the figure is based on is not specified.

Climate stations operated by Comisión Nacional del Agua (CNA) are distributed over the larger part of the model area. Locations and station names are depicted in Figure 2.11. The stations measure temperature, precipitation, pan-evaporation, pressure and wind speed; however not all the stations have all facilities, and their time of operation is also very varying. Some of the stations have been in operation
as far back as 1952, but often records are missing for whole months and years and for a large part of the stations records only date back to the late 1990's.

Average precipitation rates in the model area range from around 850 mm/year up to around 1500 mm/year based on observations from the CNA climate stations. The monthly variation in precipitation for four climate stations representing different parts of the model area is displayed in Figure 2.12 along with the average monthly precipitation for all stations in the model area. The four stations have been selected based on location and length of records. The locations of selected climate stations are highlighted in Figure 2.11. The graph in Figure 2.12 shows a strong annual variation in precipitation with the largest amount of precipitation falling in June to October.



Figure 2.11. Climate stations in the model area (based on data from CNA, Chetumal) displayed on background map from SRTM (USGS, 2004). Legend unit is m.a.m.s.l.

#### 2 – Description of Model Area



**Figure 2.12**. Monthly variation in precipitation for selected climate stations in Quintana Roo (see Figure 2.11). Data from CNA, Chetumal.

Precipitation is below average at X-Pichil located in the low-lying north-western part of the model area approcimately 100 km from the coast, whereas the largest rainfall is at Lázaro Gárdenas in the southern part of the model area. Besides the large spatial variability in precipitation in the model area the data from the CNA climate stations also reveal a strong inter-annual variability of several hundred mm/year, as also mentioned by e.g. Villasuso & Ramos (2000) and Olmsted & Alvarez-Buylla (1995).

In Appendix A figures of the spatial yearly and seasonal precipitation distributions are shown. They have been made using spatially distributed data from IWMI (2006). It is also these data which have been used as precipitation input to the regional hydrological model presented later in this report due to the better coverage of the whole model area with these data.

Potential evapotranspiration rates are estimated to be rather high in the model area. Figure 2.13 shows that the estimated potential evapotranspiration rates in the model area range between 1300 mm/year and 1700 mm/year when estimated with the Thornwaite method. Based on Figure 2.13 potential evapotranspiration rates are expected to be in the lower end around the Sian Ka'an Biosphere Reserve, however only one measurement is available from this area. The higher rates are expected to be found north-west of Felipe Carrillo Puerto.



**Figure 2.13**. Spatial distribution of potential evapotranspiration rates in mm/year. The figure shows values from INEGI (1983), estimated using the Thornwaite method, cited and shown in Villasuso & Ramos (2000).

Figure 2.14 displays the average monthly variation in precipitation compared with the average monthly potential evaporation for the model area, based on CNA's measured data. The graph shows that the potential evaporation exceeds the precipitation for a large part of the year. Since pan evaporation is proportional to potential evapotranspiration, it is not surprising that potential evapotranspiration calculated in the pre-thesis project with Hargreaves' equation using temperature data from Global Surface Summary of Day (NCDC, 2006b) for a single climate station, showed a similar pattern. It is seen that potential evapo(transpi)ration rates are expected to be highest in March to August and lowest in December to February.



**Figure 2.14**. Average monthly variation in precipitation and potential evaporation based on data from all CNA climate stations in the model area (see Figure 2.11). Data from CNA, Chetumal.

Generally on the Yucatan Peninsula, it is expected that up to 85% of the precipitation is evapotranspired, due to a dense vegetation cover and high temperatures (Villasuso & Ramos, 2000; Alcocer *et al.*, 1998), however Beddows (2004) estimated that the evapotranspiration loss could be as low as 40% on the Riviera Maya due to the high infiltration rates, especially during intense precipitation periods.

Generally, the recharge is expected to have a highly seasonal variation due to the seasonal variations in rainfall. The high degree of uncertainty that characterizes currently available estimates of evapotranspiration also means that reliable estimates of recharge are not available, and that recharge can range from 15% to 60% of total annual precipitation. The actual recharge rate depends to a large extent on whether the vegetation is able to tap water from the saturated zone, as recharge rates have been estimated to be 60% of annual precipitation in a carbonate aquifer where the vegetation was decoupled from the saturated zone due to a 30 to 180 m thick vadose zone (Mink & Vacher, 1997, cited in Beddows, 2004). The vadose zone in the model area is expected to be > 20 m thick, except in the near-coastal zone (Beddows, 2004). The ability of the vegetation to tap water from the water table is discussed later in this chapter.

Temperatures in the model area have little variation both spatially and temporally. Average monthly temperatures measured by CNA range from about 23°C in December-January to around 27°C in May-September with an overall annual average temperature of about 26°C. Figure 2.15 shows the average monthly variation in temperature over the model area for the selected climate stations along with the average monthly temperature calculated from data for all climate stations in the model area. The highest temperatures are found at X-Pichil, whereas temperatures at the other stations do not deviate significantly from the average.



**Figure 2.15**. Average monthly variation in temperature for selected climate stations in Quintana Roo (see Figure 2.11). Data from CNA, Chetumal.

Warm humid winds from a predominantly east/north-eastern direction pass over the model area (Back & Hanshaw, 1970). Winds are blowing practically all the time and wind speeds of up to 100 km/h are not uncommon. Hurricanes and tropical storms are another important aspect of the climate in the Caribbean region. Especially the Caribbean Yucatan coast is frequently affected by these storms. The hurricane season extends from June to October with the maximum activity in September, where most hurricanes of highest intensity (category 5) are recorded (Jáuregui, 2003). On average there were 5.8 hurricanes per decade during the past century with hurricane activity peaking around the 1970's. However, while the number of landfalling hurricanes in the Gulf of Mexico and Caribbean region has declined since the 1980's, the number of landfalling tropical storms has markedly increased (Jáuregui, 2003).

Trajectories of all known hurricanes and tropical storms in the western Caribbean region between 1851 and 2005 are depicted in Figure 2.16. The storms typically pass through the Yucatan Channel between the Yucatan Peninsula and Cuba or pass the Yucatan Peninsula in a western northwestern direction. In the period from 1951 to 2000 the number of hurricanes (all categories) that made landfall on the Gulf of Mexico/Yucatan Caribbean coast was 27, corresponding to  $\sim 9\%$  of all hurricane activity in the Atlantic, with 13 making landfall in Quintana Roo (Jáuregui, 2003). Very few of the hurricane centres have passed directly through the model area, which has predominantly been directly passed by tropical storms and tropical depressions.



**Figure 2.16**. Trajectories of hurricanes and tropical storms from 1851 to 2005 in the western Caribbean (NOAA CSC, 2006). H1-5: Hurricane categories 1-5, TS: tropical storm, TD: tropical depression, SS: subtropical storm, SD: subtropical depression, E: extratropical storm, L: tropical low, D: tropical disturbance: W: tropical wave.

## 2.2.4 Groundwater

#### 2.2.4.1 Fresh and Saline Groundwater

The aquifer of the Yucatan Peninsula can be described as an unconfined, young coastal karst aquifer, consisting of a thin freshwater lens floating on top of higher density saline water (Villasuso & Ramos, 2000). The aquifer is recharged primarily by precipitation. Villasuso & Ramos (2000) state that recharge follows the rainfall distribution pattern, and that recharge especially takes place at the highest points on the Peninsula in the states of Campeche and Quintana Roo. Thus, the water flows underground from the elevated areas in the interior part of the Peninsula towards the eastern, northern and western coasts, where it discharges through a series of terrestrial and submarine springs (Villasuso & Ramos, 2000).

Besides recharge by precipitation, the aquifer also receives an inflow of water from outside the Peninsula, according to Lesser (1980, cited in Villasuso & Ramos, 2000). The state of Quintana Roo is estimated to receive about 2500 million m<sup>3</sup>/yr as inflow from outside the Peninsula (Lesser, 1980, cited in Villasuso & Ramos, 2000). It is not known how large a part of this actually flows into our model area, although it is expected that it would be a larger part of this, since our model area includes most of the border between Quintana Roo and the areas outside the Peninsula.

The aquifer is situated rather close to the topographical surface, especially in the coastal region, where the vadose zone is only  $\sim$ 2-10 m thick. Further inland the vadose zone increases to 20-50 m thickness (Beddows, 2004; own field data). Recharge infiltrates to the aquifer through the vadose zone, but may be stored here for a shorter or longer time before reaching the water table, if the recharge rate exceeds that

which can be transmitted by the geological medium (Ford & Williams, 1989, Bakalowicz, 2005). It is expected that in the coastal zone it can take from tens to hundreds of days for the recharge to reach the aquifer (Beddows, 2004).

Few data have been found on the hydraulic gradient in the model area. However, Moore *et al.* (1992) report a maximum hydraulic gradient to be 130 mm/km, measured in an area 8 km south of Playa del Carmen. Beddows (2004) found a hydraulic gradient of 58 mm/km based on a measurement of water level in a well 32.5 km from the coast on the road between Tulum and Cobá. A study conducted in the north-western part of the Peninsula found a hydraulic gradient of about 7-10 mm/km (Marín, 1990, cited in Alcocer *et al.*, 1998). The differences in the hydraulic gradient may be due that unconfined karst aquifers may exhibit local and regional depressions caused by the presence of conduits, which locally can attract a larger part of the water, thus causing a depression in the water table (Ford & Williams, 1989; Milanović, 2004).

Independent, perched aquifers are found in the elevated areas in the interior of the Peninsula. That they are not hydraulically connected to the regional aquifer is evident from the low salinity of their waters, which indicates recent infiltration. Also the depth to these perched aquifers below ground surface is smaller than the depth to the regional aquifer. Some of these perched aquifers are under artesian pressure (CNA, 2001).

The saline water beneath the Yucatan freshwater lens is mainly saltwater intruding from the sea through underground conduit systems as well as the matrix, but especially in the area with the oldest geology, dissolution of evaporites present in this sediment also makes part of the groundwater saline (Pacheco, 2001; Villasuso & Ramos, 2000).

The weight of the freshwater depresses the underlying saline water resulting in a lenticular shape of the interface between fresh and saline water (the halocline). The boundary that separates the freshwater lens from the underlying saltwater is a freshwater/saltwater mixing zone of variable thickness. The mixing zone is thickest closest to the coast but decreases inland to a rather sharply defined layer as the effect of tide and turbulence due to conduit discharge diminishes. The thickness and location of the halocline is described in more detail in the subsection on "Caves" later in this chapter and Chapter 4.

There is a circulation of saline water under the Yucatan Peninsula. Four principal drives to saline circulation based on observations in the Bahamas have been identified by Whitaker and Smart (1993; cited in Beddows, 2004):

- Buoyant circulation (density)
- Sea surface height (elevation head)
- Reflux (density)
- Temperature

The buoyant circulation suggests that the brackish water that results from the mixing of saline water and freshwater in the aquifer will rise along the halocline towards the coast. The loss of saline water under the Peninsula is compensated for by an inflow of seawater at depth. Inflow of seawater can also be generated by a difference in oceanic head on each side of the limestone platform, which may be generated from ponding of water on one side due to e.g tide or wind.

Another possible driver for saline circulation is evapotranspiration from shallow coastal water bodies with limited connection to the sea. Due to evaporation the salinity and thus the density of these waters will increase. This higher density water will sink and displace saline water of lower density. Lastly, a flux of lower density saline water can occur from the interior of the Peninsula and outwards due to geothermal heating that decreases the density of the saline water.

Beddows (2004) has identified two types of saline flow in the Caribbean part of the Yucatan Peninsula aquifer. The first is a shallow two-way flow corresponding to the tidal frequency with an effect that has been observed > 9 km inland. The other is a continuous inflow at ~5 m to ~45 m depth suggesting a saline circulation through the platform with discharge in the Gulf of Mexico.

### 2.2.4.2 Hydrogeology

The hydrogeologic properties of karst display a high degree of heterogeneity due to the various processes that cause dissolution and destruction of the carbonate rock resulting in significant secondary porosity features (Ford & Williams, 1989; Milanović, 2004). The principal dissolution processes are *distributed dissolution* that takes place when rainwater meets the carbonate rock and continues during infiltration; and *mixing zone dissolution* that – as the name implies - takes place in the saltwater/freshwater mixing zone. The latter is caused by the fact that when saltwater and freshwater both saturated with calcite is mixed, and the two waters have a different partial pressure of  $CO_2$ , the mixture becomes sub-saturated with calcite and more can therefore be dissolved in this mixing layer than outside it (Appelo & Postma, 2005). The dissolution of the carbonate rock may create conduits of varying size that may develop into vast networks. Dissolution especially occurs in connection with other secondary porosity features such as bedding planes, joints, faults and fracture traces (Ford & Williams, 1989).

Basically, the karstified geological medium consists of 3 overall components: a rock matrix, a fracture network and a conduit network. The difference between the two latter is the size of the openings. White (2003) defines fractures as having openings ranging from 0.01 or 0.1 mm to 10 mm, while those of conduits may be from 10 mm to tens or even hundreds of meters. Figure 2.17 schematically illustrates the three components of a karst aquifer and also shows aquifers with only one or two of the components.



**Figure 2.17**. Different types of aquifers -a) A rock matrix with only primary porosity, b) a rock matrix with joints or fractures, i.e. both primary and secondary porosity, and c) a rock matrix with fracture and conduit networks, i.e. a karstified aquifer with both primary and secondary porosity. From Worthington (2003).

Due to the dissolution water may flow in the rock matrix and in the fractures and conduits. The degree of flow in the *matrix* depends on the primary porosity, which here means the porosity created as the rock was formed by sedimentation. Although this can be very small in other karst terrains, primary porosity is

not negligible on the Yucatan Peninsula (Milanović, 2004). The number and size of the *fractures and conduits* determines the secondary porosity.

The flow of water in the aquifer depends on the interconnectedness of the voids in the geologic medium, both in the primary porosity and the secondary porosity. When the size of the pore spaces increase and the more they are interconnected, the higher the permeability becomes, and thus the hydraulic conductivity and the aquifer's ability to transmit water also increases (Ford & Williams, 1989). The transmissivity, i.e. the aquifer's ability to transmit water, is a function of the hydraulic conductivity and the thickness of the aquifer and therefore the transmissivity of karst aquifers also varies widely in space.

Only little is known about the properties of the limestones in our model area, as most studies of the area's limestone porosity and permeability concentrates around Merida and the Ring of Cenotes in Yucatan State. In Merida, the porosity has been found to range between ~7% and ~41% with an average of 23% based on samples from 30 boreholes (González-Herrera, 1984, cited in Beddows, 2004, and in Steinich & Marín, 1997). The variation in porosity is especially seen in the upper 40 m, whereas the porosity of the limestone at lower depths was seen to be fairly constant around 24%. The same study showed a fairly consistent average permeability of  $3.1 \cdot 10^{-1}$  m/day at depth, but with a decrease of two orders of magnitude in the top 5 m (González-Herrera, 1984, cited in Beddows, 2004).

A study of limestones in the Caribbean coastal zone, indicated a depositional porosity of the carbonates in the range from 29% to 50%, but the porosity has generally been reduced to 14%-23% due to cementation (Harris, 1984 cited in Smart *et al.*, 2006). There are no studies of the porosity of limestones in the interior parts of the Peninsula, however the old geological formations here (Mesozoic and Paleozoic) are "extensively" cemented (Smart *et al.*, 2006) and must therefore be expected to have lower porosity than younger formations closer to the coast.

The aquifer has a high transmissivity, due to the dissolution features. Transmissivities have been measured by pump tests, from ca. 0.5 m<sup>3</sup>/(s·m) to more than 1.9 m<sup>3</sup>/(s·m), values which are cited to be "extreme transmissivities (which) are high, even for limestone aquifers" (Doehring & Butler, 1974<sup>3</sup>). Other data on the transmissivities of the aquifer have not been found.

Overall, the matrix and the fracture networks have a high storage capacity but low flow velocities, whereas conduits have low storage capacities but high flow velocities (Atkinson, 1977; Worthington, 2003; Cheng & Chen, 2004). This is because in the matrix and fracture network there may be many pore spaces which are not interconnected but may still store water, and because flow between the pore spaces is confined to tiny interconnections, where friction forces are large. The relatively much smaller friction force on water bodies in conduits allows water velocities to be much larger in conduits, where the flow may even become turbulent.

In a study of the Caribbean part of the Yucatan aquifer where the presence of conduits is very distinct, Worthington (2000 cited in Beddows, 2004) found that the matrix accounts for 96.6% of the storage of the aquifer, whereas almost all flow (99.7%) takes place in conduits. A more thorough description of caves and conduits in the model area will be given in section 2.2.6.

The hydraulic conductivity, K, of the aquifer medium varies spatially due to the heterogeneity of the karst. Figure 2.18 gives K-values which have been used or calculated in studies of the Yucatan Peninsula.

<sup>&</sup>lt;sup>3</sup> Values have been recalculated from the unit "gallons per day per foot".

The values in Figure 2.18 have mainly been determined using hydrological models or calculated based on water velocity data and range from  $1 \cdot 10^{-6}$  m/s to 6 m/s. Most of the values have been estimated for locations in the north-western part of the Peninsula, i.e. the Merida and Ring of Cenotes area. High values have been used in mathematical models, whereas the smallest value stems from laboratory measurements and may be several orders of magnitude smaller than in-situ values (González-Herrera *et al.*, 2002).

In the only study from a site relatively close to our model area (9 km south of Playa del Carmen), Moore *et al.* (1992) calculated a K of 0.65 m/s from Darcy's Law using measured water velocity and measured hydraulic gradient, as well as estimated porosity of 0.40. A K of 0.19 m/s was calculated from Darcy's Law using measured water velocity and measured hydraulic gradient, as well as estimated porosity of 0.12. The latter porosity is found in borehole samples from a location near Caleta Xcaret.



**Figure 2.18**. Scale of hydraulic conductivity, *K*, mentioned in the literature for limestones on the Yucatan Peninsula (point values or intervals indicated by maximum and minimum values). Numbers refer to the source of the data which can be found in Appendix B.

Due to its heterogeneity, the porosity and the hydraulic conductivity of carbonate aquifers with significant dissolution depends on the scale of observation. I.e. if one studies a small piece of the rock in the laboratory it will display other average hydraulic properties than if a large regional aquifer basin is studied (Kiraly, 1975, cited in Ford & Williams, 1989), i.e. a high hydraulic conductivity can be expected for a regional-scale hydrological model.

There may also be a difference in the longitudinal and transverse hydraulic conductivity for a location, . González-Herrera *et al.* (2002) cite a study of 56 cenotes and caverns in Yucatan investigated by Sánches (1999) that found that the direction of maximum K was correlated with the main orientation of caves. This can be important to include in hydrological models.

# 2.2.5 <u>Surface Water</u>

In the model area, some surface water bodies exist despite the general high permeability of the limestone. First of all, there are the cenotes, which are the karstic sinkholes developed by dissolution of the limestone geology and/or by collapse of cave ceilings. The cenotes thus are direct openings to the groundwater table. On the whole Peninsula the number of cenotes is estimated to be more than 7000 (Speleonet, 2005). Cenotes are not spread evenly around the Peninsula, but are rather usually found in groups or in a line after each other (González-Herrera *et al.*, 2002).

Other surface waters in the model area are lagoons and wetlands near the east coast, and lakes, some of which have formed along fault lines, e.g. Lake Bacalar, located in one of the Rio Hondo faults. These surface water bodies all contain fresh groundwater, although the lagoons and wetlands on the east coast, notably in Sian Ka'an, are brackish due to mixing of groundwater and saltwater from the sea (Chiappa-Carrara *et al.*, 2003). Wetlands constitute roughly one third of the area of Sian Ka'an (CONANP, 2006; UNESCO, 2006). No detailed maps on the extent of the wetlands in Sian Ka'an have been obtained. The limited data found on the water levels in a lagoon in Sian Ka'an will be presented in Chapter 5.

The great Lake Bacalar, also mentioned previously, was investigated by Perry *et al.* (2002), who showed based on groundwater geochemical analysis that the lake is not connected to the sea. This is surprising since other dissolution features near the coast, e.g. the caves in the Tulum region, are often found to be influenced by the sea water. Perry *et al.* (2002) also found that there is a significant groundwater flow in Lake Bacalar. Thus, the flow must be directed elsewhere than towards the coast. Perry *et al.* (2002) explained the lacking connection to the coast by the fact that Lake Bacalar is fed by waters with a high gypsum-content, due to the gypsum-rich older geology in this southern region. This together with supersaturation of its waters with respect to calcite gives a geochemical composition which is not capable of dissolving limestone, and thus underground caves from the fault has not formed directed towards the coast.

The model area contains a river, namely the Rio Escondido. However, no information has been found on this river, despite enquiries at the relevant water authorities in Mexico. Part of the river seems to be ephemeral according to ITMB (2005) and a figure from INEGI (2006a) shown in Figure 2.19. The larger river Rio Hondo follows the southern boundary of our model area and will therefore not be dealt with here.

Finally, there are several areas in the model area that are subject to inundation. These swamps are located at elevations well above sea level. Many of them may be completely dry until the summer months (e.g. July/August), while at later times in the year, water levels may reach up to 3 meters above the ground (Merediz Alonso, pers. comm., 2006). Field observations confirmed this, exemplified by the height of the bridge above one of these intermittently flooded areas, as displayed in Figure 2.20, and height of observed culverts etc. The inundated areas have a special type of vegetation distinct from the surrounding areas (Merediz Alonso, pers. comm., 2006). Merediz Alonso observed that when these areas are inundated, indundated "arms" stretch towards the area of Sian Ka'an, and may sometimes also recharge into cenotes (Merediz Alonso, pers. comm., 2006). No further detailed descriptions of the flooded areas have been found in the literature, but their locations according to a map from INEGI (2006a) are shown in Figure 2.19.

Inland, also several perennial lakes located at elevations well above sea level can be found. By measuring the specific electrical conductance in some of these lakes it was found that their conductance is very low, even lower than that of the calcite-saturated groundwater. This indicates that the waters of these inland lakes are primarily rain water (the details of the measurements are displayed in Appendix C). Perry *et al.* (2002) found that the lake levels only recovered slowly after storm events, which supports the hypothesis mentioned in the Geology-section of this chapter, that the lakes (and swamps) may be underlain by a material of low permeability, such as ejecta. In addition, Perry *et al.* (2002) mention that the ejecta layers are likely to be found together with a clay-rich altered survite layer, which thus also has low permeability.



**Figure 2.19**. Map of areas subject to inundation (green spots) as well as main rivers in Quintana Roo. From INEGI (2006a).



**Figure 2.20**. Culvert and bridge in areas which are subject to inundation part of the year. Located between the villages Chan Santa Cruz and Petcacab in Quintana Roo, roughly 40 km southwest of Felipe Carrillo Puerto. Note the height of the bridge which indicates maximum possible level of inundation. Ms. Rahbek positioned left of the bridge to give the scale.

#### 2.2.6 <u>Caves</u>

Both submerged and dry caves are found in abundance various places in the model area. This subsection will focus on the known underwater caves of the area, due to their importance for the hydrological system. The information is provided in order to also understand what simplifications of the systems will be made when setting up the simple generic conduit-matrix model in Chapter 8.

Generally, not much is known about the cave systems in the area. Only a few published studies are available on the hydrology, morphology and structure of the caves, notably Beddows (2004) and Smart *et al.* (2006). The principal source of information on the caves is the scuba-diving cave explorers of the area. Scuba divers started to explore the underwater caves about 20 years ago and are making line maps of the caves, documenting coordinates and directions of the caves, depths of cave ceilings and bottoms, as well as the location of the halocline. Occationally, also the strength and direction of water flow is noted. Also detailed cave maps have been made of selected caves, with more detailed indications of dimensions, breakdown areas, speleothems etc. (e.g. Coke & Sutton, 1993). All these explorations are valuable in order to get to understand the system, however they do have various sources of error. For one, because cave diving is dangerous the quality of the data may depend on the conditions of the cave in that particular section, as the prime focus of a diver is of course to maneuver safely in this potentially

hazardous environment. In addition there are sources of error, such as data error from GPS devices, uncertainties of compasses and depth gauges, and the drift of the magnetic north pole over the years. Nevertheless, the cave surveys give extremely valuable information on the caves. In addition, qualitative descriptions from the divers can be very useful to understand the system.

The information on caves presented in this chapter comes from the few publications available on this topic as well as personal communication with cave divers and a geologist familiar with the area. At times, personal communications may be contradictory. In order to take this into account, only statements which were not contradicted by other people's statements in our interviews are presented here.

#### 2.2.6.1 General Characteristics of the Underwater Cave Systems

Some of the world's longest underwater cave systems have been discovered and explored in the northeastern part of the model area, in an area which roughly stretches from 15 km southwest of Tulum to 15 km northeast of Tulum at Xel Ha. These systems include the world's two longest underwater cave systems – Ox Bel Ha and Sac Actun (QRSS, 2006). Figure 2.21 displays the location of a large part of the known underwater cave systems, which have been mapped by cave divers.



**Figure 2.21**. Underwater caves mapped by cave explorers in the area near Tulum, as shown in Smart *et al.* (2006). Data originate from the Quintana Roo Speleological Survey (QRSS) and have been collected by surveyors: A. Alvarez, B. Birnbach, S. Bogaerts, G. Brown, K. Davidson, F. Devos, M. Jasper, C. Le Maillot, D. Lins, M. Madden, A. Matthes, S. Meacham, B. Quattlebaum, S. Richards, B. Philips, D. Riordan, R. Schmittner, S. Schnittger, C. Stevens, C. Stanton, P. Thomsen, G. and K. Walten, The Dark Shamrock Team.

This area with known extensive underwater caves stretches from the east coast to roughly 12 km inland, and is characterized by a high cenote density, roughly one cenote every 300 m, which often is a surface manifestation of extensive underwater passages (Coke, pers. comm., 2006; Schmittner, pers. comm., 2006; Meacham, pers. comm., 2006; Beddows, 2004; Devos, pers. comm., 2006). Further inland, beyond the Holbox fracture, dives into known cenotes have thus far generally revealed no horizontal passages, and cenotes are mostly vertical holes without lateral connections (Coke, pers. comm., 2006; Schmittner, pers. comm., 2006; Meacham, pers. comm., 2006). North of Xel Ha, the known cave systems are more localized and not as laterally extensive, since they end more quickly, or narrow into smaller caves that cannot be entered by divers (Coke, pers. comm., 2006). They thus seem different than the longer caves explored south of Xel Ha, according to the divers. The area of known extensive underwater caves may be compared with the geological map of Ward (no year), shown in Figure 2.22. The figure shows the carbonate rock surface geology in the area, distinguished by crusts ("caliche") between the sequences of deposited layers, which formed when that part of the formation was the surface of the geological layer. The ages of the layer units are not yet adequately determined; however at least the 3 types closest to the coast are regarded to be of Pleistocene origin (Ward, no year). According to this map it seems that the areas of extensive cave development correspond to these 3 coastward geological units C, D and Upper Pleistocene-Holocene undifferentiated. Unit C is skeletal grainstone, packstone and wackestone with common coral patchreefs while Unit D is coral-reef rock with reef-lagoon limestones on the landward side (Ward, no year). Thus, the area of Pleistocene geology may correlate with extensive cave development, since also the area beyond which no extensive caves have been found (beyond "Carwash" cenote) corresponds with the inland boundary of the Pleistocene, according to Shaw (pers. comm., 2006). According to Ward (2003) the metastable mineralogy of the Upper Pleistocene formations causes them to be prone to near-surface groundwater interaction to a large extent. In addition, cenotes near Akumal on the eastern coast reveal limestone dissolution in the Pleistocene cover and in underlying Miocene strata (Shaw, 2003). Besides the possible importance of geology on the cave formation, also the specific discharge through the rock is a determining factor for the development of the caves (Smart et al., 2006).

The cave systems of the area are anastomosing network systems and the pattern of the caves suggests that porous matrix flow is important in the development of the caves, as opposed to the caves types, which would develop in a non-permeable matrix (Smart *et al.*, 2006). Smart *et al.* (2006) find that the intersections of caves have occurred as random processes. The cave conduits are interconnected to a large extent, and create a type of spongework in certain areas (Devos, pers. comm., 2006; Beddows, 2004). The general direction of the conduits is perpendicular to the coast, i.e. northwest-southeast.

As seen on Figure 2.21 many cave systems have their outlets at the coast, however not all. A large system such as Dos Ojos (the world's 4<sup>th</sup> longest underwater cave system) seems to have no sea connection, as it is located 4 km inland (Schmittner, pers. comm., 2006). Several lagoons along the coast north of Tulum are all outlets for ground water flow from the catchments. In addition, crescent-shaped bays are believed to have formed due to dissolution of the limestone rock as freshwater mixes with saltwater, and may therefore indicate an area of focused groundwater outlet (Shaw, 2003; Shaw, pers. comm., 2006), In these bays thousands of tiny outlet holes are found discharging brackish water (Coke, pers. comm., 2006).

Breakdown areas are common in the underwater caves of the area and may manifest themselves as cenotes at the ground surface, if the roof of a conduit system has collapsed completely. Around cenotes, diversion passages may often be found, and thus cave patterns can be more complex around cenotes, because the breakdown areas can change the hydrology of the area (Smart *et al.*, 2006).

There are at least 2 levels of caves in the area. However, the deeper caves (e.g. located at 90-95 m depth) are only little explored at this time, and in these caves saline water is circulating (Coke, pers. comm., 2006; Smart *et al.*, 2006). In the following, only the general pattern of caves containing freshwater is described.



Figure 2.22. Geological map of the Tulum area, as drawn by Ward (no year).

Generally, the caves become deeper inland. Median depth is 14 m, and inland depths rarely exceed 25-28 m (Coke, pers. comm., 2006). Inland caves have average maximum depths of  $22.3 \pm 8.7$  m, while coastal caves have an average maximum depth of  $11.8 \pm 6.2$  m (Beddows, 2004). The increase in depth inland is not a constant increase, but modulated by fluctuations. This is probably due to the various processes that formed the caves, and which are explained in detail in Smart *et al.*, (2006). This depth variation is illustrated in Figure 2.23, which shows a schematic drawing of a generalized cave pattern in the x-z plane, based on the pattern of the Sac Actun system (Schmittner, pers. comm., 2006).



**Figure 2.23**. Schematic drawing of general depth variations, based on the pattern of the Sac Actun system. Not to scale. Modified from illustration by Schmittner (pers. comm. 2006).

Outlets are often located in very shallow water, as the figure illustrates, i.e. at around 3-4 m depth in the sea bottom, less than 50 m from the coast (Schmittner, pers. comm., 2006; Beddows, 2004). Water in the outlets is always brackish, due to mixing of fresh groundwater and sea water. However, about 70-80 meters from the coast into the ocean, there is a platform wall in the sea bottom. In this wall along the coast, large outlet holes may also be found at approximately 90 m depth (Coke, pers. comm., 2006). This may be an outlet hole of the deeper cave systems, although presently no detailed information on this is available.

#### 2.2.6.2 Development of the Caves

Based on sediment fill, speleothem occurrence and an analysis of the depths of cave ceilings, Smart *et al.* (2006) suggest that the development of the underwater caves of the area must have occurred during several phases, and that the fluctuating sea levels due to glaciations have had a large impact on the development of the caves. They suggest that the extent of the cave systems is a function of the total coastal discharge of freshwater as well as of the total time of development (Smart *et al.*, 2006). Smart *et al.* (2006) list several processes which may have been important for the formation of the caves, of which dissolution due to mixing of freshwater and saltwater is believed to be the most important one. Further description of this mechanism can be found in the pre-thesis.

The cave systems are often found to form along fractures and bedding planes. Thus, cave maps often indicate presence of bedding planes (e.g. Coke & Sutton, 1993; GEO & CINDAQ, 2003). Development along fractures is also typical in the Ox Bel Ha system (Schmittner, pers. comm., 2006) and in the newly discovered cave system inside the Sian Ka'an Biosphere Reserve (Le Maillot, pers. comm., 2006). In fact, up to 95% of the caves in the area may be fracture-controlled (Coke, pers. comm., 2006).

A further discussion of the development of the cave systems in the Tulum area may be found in Smart *et al.* (2006).

# 2.2.6.3 Cave Morphology, Dimensions and Flow

The underwater cave systems in the area are characterized by sudden passage terminations and sudden variations in conduit size. Dimensions and cross-sections may vary tremendously in the caves, from restricted areas to wide rooms fairly close to each other (Smart *et al.*, 2006; The Cambrian Foundation, 2006; Coke, 2001; Coke & Sutton, 1993; Coke *et al.*, 1993; Coke & Young, 1990). Therefore, it can be difficult to generalize cross-section types and dimensions. However, two main morphologies exist in the systems: elliptical tube passages, which are wider than high, and fissure passages, which are higher than wide. The former type has a large lateral continuity (100 m to 1 km) while the lateral continuity of the latter is only tens of meters (Smart *et al.*, 2006). In addition, breakdowns are common in the cave systems, as mentioned earlier.

A distinction can be made between two overall cave types of the area – the inland caves (extending from the coastal zone and up to about 12 km inland) and the coastal caves. No precise definition has been found on the extent of this coastal zone. Inland caves are large, and typically of the elliptical tube form, while coastal caves are small, commonly like fissure passages, and their pattern is more maze-like (Schmittner, pers. comm., 2006; Beddows, 2003; Smart et al., 2006). The inland caves have developed in at least two phases, and have more areas of collapse as well as sediment infill, while coastal caves seem to have fewer development phases than the inland, perhaps only one, according to Smart *et al.* (2006). Coastal caves are more often formed along fractures, while inland caves have a more complex, anastomosing pattern, which may be due to difference in fracture density and/or due to difference in the length of time over which the systems have developed (Smart et al., 2006). The flow direction of the coastal caves depends on the tide, and some caves along the coast are in fact parallel to the coast, and not perpendicular to it (Schmittner, pers. comm., 2006). In addition, coastal caves generally have less decoration (speleothems) than the inland caves (Schmittner, pers. comm., 2006; Le Maillot, pers. comm., 2006). The coastal caves are known to be actively developing at present times, and are actively modified by the mixing zone, since for instance presence of the mixing zone often correlates with an incision in the cross-section of coastal caves (Smart et al., 2006; Schmittner, pers. comm., 2006).

Typical dimensions of fissure passages are 0.5 to 2 m in width, 5 to 10 m in height. For elliptical tubular passages, the dimensions may be much more diverse, from 1-2 m in width to more than 30 m, and the width is then typically 1.1 to 5 times the height (Smart *et al.*, 2006). Especially there seems to be a divide about 4 km from the coast, inland of which the large trunk passages of caves can be found (Coke, pers. comm., 2006). In mapped inland cave systems, heights from floor to ceiling may e.g. be from 1 to 7.5 m (Carwash),  $\frac{1}{2}$  to 9 m (Escueleto), 1 to 7.5 (Maya Blue), 1 to 11 m (Muknal R. S.) (Coke, 2001; Coke & Sutton, 1993; Coke *et al.*, 1993; Coke & Young, 1990). Outlets at the coast typically have smaller dimensions than the cave systems, e.g. 4-6 m in diameter (Beddows, 2004). Piles of rock resulting from breakdowns may be more than 20 m high (Smart *et al.*, 2006).

The Ox Bel Ha system and the Caapechen system are particularly large systems (Devos, pers. comm., 2006; Le Maillot, pers. comm., 2006). The latter system is located inside the Sian Ka'an Biosphere Reserve.

The Caapechen system is newly discovered. Currently, 6128 m of cave has been mapped there but the cave is known to continue further (Le Maillot, pers. comm., 2006). According to divers' reports this cave system is notably different from the systems explored further north. The geology seems different, with clearly defined tunnels and a very solid ceiling which has very little seepage through it. In contrast, due to the sponge-like characteristics of the geology around the caves further north, seepage through cave walls is very characteristic there. The flow in the Caapechen system is very large, larger than what has even been encountered in the Ox Bel Ha (Le Maillot, pers. comm., 2006; Devos, pers. comm., 2006). Also, the dimensions are larger – at some places height can be up to 10-12 m, while the width may be up to 45 m (Le Maillot, pers. comm., 2006). In addition, the main passage direction is south-southwest, unlike the northwestern direction of caves further north. The water in the Caapechen system also is found to flow from both northwestern and southwestern directions, before converging into the main Caapechen passage, and such a pronounced flow from southwest has generally not been seen in other cave systems in the area (Le Maillot, pers. comm., 2006; Thomsen, pers. comm., 2006). The Caapechen system has a rapid drop in depth to about 30 m, which is very rare for explored caves in the model area (Schmittner, pers. comm., 2006), and in addition, the depth of the halocline also increases very fast compared to in the other known cave systems (Le Maillot, pers. comm., 2006). The Caapechen system is the first cave system in Sian Ka'an which is being explored by the cave divers, but other outlets have been found in the Reserve, which means that it is likely that there may be more Caapechen-like systems found elsewhere in the Sian Ka'an Biosphere Reserve (Le Maillot, pers. comm., 2006).

In general, the flows of the known cave systems are largest in the Ox Bel Ha system and in the Caapechen system. Flow in the other systems besides Caapechen is mainly from the northwest towards the coast. Only in one known inland branch of the Ox Bel Ha is flow from the southwest (Devos, pers. comm., 2006; Grupo de Exploración Ox Bel Ha & CINDAQ, 2003). In addition, one line of cave has currently been explored, which shows a weak flow from the Ox Bel Ha system towards the southwest in the direction of the Sian Ka'an Biosphere Reserve. The area is difficult to explore for cave divers but there are plans to investigate this stretch of cave further in December 2006 (Le Maillot, pers. comm., 2006) Generally, in the Ox Bel Ha system flow is rather steady, except immediately after the rainy season. In contrast, flow in the Caapechen system varies notably. Divers have tried to correlate the Caapechen flow variations with tides and wind effect, but have not yet found satisfactory correlation with these factors. In many of the coastal caves north of Sian Ka'an, the flow is affected by the tides, and return flow can be important – especially in Ox Bel Ha, but return flow seems to have little influence in the Caapechen system (Le Maillot, pers. comm., 2006; Devos, pers. comm., 2006; Schmittner, pers. comm., 2006; Riordan, pers. comm., 2006).

Only few magnitudes of flow have been measured. These will be presented in Chapter 8 under conduitmatrix modelling.

#### 2.2.6.4 Decoration and Friction Factors in the Caves

Speleothem deposits are encountered in many of the explored underwater caves in the model area. The degree of decoration varies in space, but in general, there are more speleothems the more inland the caves are situated. Caves near the coast are often more smooth (Le Maillot, pers. comm., 2006; Schmittner, pers. comm., 2006). The speleothem deposits have an influence on the cave conduit water flow, since extensive speleothem decoration will increase the friction forces acting on the water. In addition, sediment infill and breakdown debris present in some cave sections also increases friction.

Therefore, these factors are determining for the degree of friction which will be present in a conduit system, and thus for the conveyance of water which will be possible in a particular cave stretch.

The degree of friction may be described by friction factors. The friction factor describes loss of energy due to friction with the conduit wall (head loss). It increases as the wall roughness increases or as conduits become obstructed by other material. Furthermore, it generally depends on the degree of turbulence of the water. The definition of the friction factor follows from the Darcy-Weisbach equation, which describes turbulent flow (e.g. Ford & Williams, 1989):

$$f = \frac{8R_Hg}{q^2} \cdot \frac{dh}{dl}$$
(Eq. 2.1)

where *q* is the velocity of the water [L/T], *f* is the Darcy-Weisbach friction factor [-],  $R_H$  is the hydraulic radius [L], defined by the ratio between the conduit cross-sectional area and the wetted perimeter, and *g* is the gravity acceleration [L/T<sup>2</sup>]. The Darcy-Weisbach equation is valid for steady state, turbulent flow (Pedersen, 1988). The theory behind friction factors is described further in Appendix D.

Friction factors are not well determined for the cave systems in the model area. Only Beddows (2003; 2004) has attempted to quantify friction factors in the Nohoch Nah Chich system. In her two publications, the suggested friction factors (*f*) vary widely for the same conduit segments, from 1 to 1000 (dimensionless), as may be seen from Table 2.1. However, her most recently determined friction factors are in the range of 500-1000 (dim. less) (Beddows, 2004). A higher friction factor indicates more friction, and thus more resistance to flow. The most recently determined friction factors of Nohoch Nah Chich are at a very high range compared to values from other cave systems, which range from 0.1 to 340 (dim. less) (see Table D.1 in Appendix D). This suggests that in the Nohoch Nah Chich conduits, and possibly also in the other cave systems in the area, head loss will be large due to friction.

Friction factors may be recalculated to their equivalent Manning's *M* roughness coefficient by combining the Darcy-Weisbach equation and the Manning equation, as described further in Appendix D. The resulting formula is:

$$M = \sqrt{\frac{8g}{R_{H}^{1/3} \cdot f}}$$
(Eq. 2.2)

Using this formula, it is assumed that the flow in the conduits is fully turbulent and that the conduits are somewhat rough, as Manning's formula would otherwise not be valid. Friction factors have been recalculated to Manning's M for the friction factors suggested by Beddows (2003; 2004), and is displayed in Table 2.1. The hydraulic radius as reported by Beddows (2003; 2004) has been used for these calculations.

**Table 2.1**. Conduit friction values found by Beddows (2003; 2004) for the Nohoch Nah Chich system, illustrating a wide range of possible values as they are not well determined. f is Darcy-Weisbach friction factor.  $R_H$  is hydraulic radius, as presented by Beddows (2003; 2004). M is Manning's M roughness coefficient, calculated by combination of the Darcy-Weisbach equation and the Manning equation, as discussed in Appendix D.

	f [-]	R <sub>н</sub> [m]	M [m <sup>1/3</sup> /s]	Cave system	Method
Beddows (2003)	1	1.25	8.5	Nohoch Nah Chich, Fr Quintana Roo, ve Mexico tr gr	Friction factor calculated using velocities established from dye tracing and assumed hydraulic gradient of 1·10 <sup>-5</sup> (dim. less).
	4	1.25	4.3		
	6	1.17	3.5		
	11	1.62	2.5		
	12	1.55	2.4		
	45	2.06	1.2		
Beddows (2003)	11	1.25	2.6	Nohoch Nah Chich, Quintana Roo, Mexico Friction factor calculate velocities established f tracing and assumed h gradient of 1·10 <sup>-4</sup> (dim.	Friction factor calculated using
	43	1.25	1.3		tracing and assumed hydraulic
	58	1.17	1.1		gradient of $1.10^{-4}$ (dim. less).
	108	1.62	0.8		
	118	1.55	0.8		
	449	2.06	0.4		
Beddows (2004)	500	1.17	0.4	Nohoch Nah Chich, Quintana Roo, MexicoFriction factor established velocities established fro tracing and a measured hydraulic gradient.	Friction factor established using velocities established from dye
	500	2.06	0.4		tracing and a measured regional hydraulic gradient.
	1000	1.17	0.3		
	1000	2.06	0.2		

Other diagnostic factors exist to describe friction in cave conduits. Thus, equivalent roughness heights,  $k_r$ , useful for applying the Colebrook & White friction formula and for evaluating roughness in relation to the depth of actual roughness features, may be found calculated for Mexican and other caves in Appendix D, so the caves in the model area may be compared with various cave systems on also this parameter.

# 2.2.7 Vegetation

The vegetation on the Yucatan Peninsula has been described as relatively homogenous (Rzedowski, 1978, cited in Sánchez-Sánchez & Islebe, 2002). The spatial distribution of the different types of tropical forest is governed by physiography and annual precipitation rates (Sánchez-Sánchez & Islebe, 2002). According to CONAFOR (2006) and CNA (2001), the vegetation found in the model area can be divided into the following categories:

• High perennial forest. Can be divided into the sub-categories high perennial forest and high subperennial forest based on the percentage of leaf loss during the dry season. This type of forests is a dense type of vegetation comprising species that are characterized by straight trunks and heights of > 30 m. The high perennial forest is a dense type of vegetation comprising species that are characterized by straight trunks (diameters between 40 and 80 cm) that do not ramify in the lower part. Most of these trees (> 75%) remain green throughout the year. The high perennial forest is found in the most inland part of the model area in southern parts of Campeche and Quintana Roo.

- Medium forest. Can be divided into the sub-categories medium perennial, medium sub-perennial forest and medium forest 'caducifolia'. The categories are determined based on the percentage of the species within the category that looses leaves during the dry season, which are < 25%, 25-50% and 50-75% respectively for the three categories. The medium forest is characterized by a height that varies between 15 to 30 m, and is mainly found in zones with between 1000 and 1500 mm of annual precipitation (Sánchez-Sánchez & Islebe, 2002). The medium perennial and sub-perennial forest types are the main vegetation types in the model area, whereas the medium 'caducifolia' forest is only found in the Sierrita de Ticul.
- Low forest: Can again be subdivided in low perennial forest and low forest 'caducifolia'. The low forest is generally very dense, with heights between 5 and 15 m. The perennial forest is seen in inundated areas on the Yucatan Peninsula, whereas the low forest 'caducifolia' is seen on the Costa Maya (the coast south of Sian Ka'an) and in the northern part of Quintana Roo.
- Hydrophilic vegetation. Covers aquatic and sub-aquatic vegetation. This vegetation is found in marshy and inundated areas of fresh or brackish waters, and distinguishes 3 types: popal, tular and coastal mangrove swamps.

The vegetation in many areas of the Yucatan Peninsula has a long history of human impact, as the forest has been burned regularly as a consequence of the traditional Mayan slash and burn agriculture (milpa), which is still practised throughout the model area today.

#### 2 – Description of Model Area



Figure 2.24. Map of main vegetation types in Quintana Roo, from INEGI (2006a)

A rough division of the main vegetation types in Quintana Roo is shown in Figure 2.24. Based on our own observations, the vegetation in the model area can be described as mainly medium forest mixed with milpa fields around the villages and more extensive agricultural areas around Chetumal and south of José Maria Morelos. Mangrove and savannah (sabana) has been observed in the Sian Ka'an Biosphere Reserve. Even at the end of the dry season (April) the forest appears green. Typical types of vegetation observed during the field trip are depicted in Figure 2.25.



Figure 2.25. Different types of vegetation encountered in the model area during the field trip. From top left: perennial forest; savannah; mangrove and low forest.

Little is known of how deep the vegetation penetrates into the subsurface. This is however a highly important issue with regard to estimations of evapotranspiration, since the availability of water is by nature a controlling factor for the amount of evapotranspiration that can be expected.

Sánchez-Sánchez & Islebe (2002) carried out a phytosociological study of the plant communities found along a 450 km transect in Quintana Roo. The study showed that the distribution of the different plant communities were highly dependent on their preference for specific soil types, soil depth, percentage of rocks and precipitation. We have attempted to find typical root penetration depths in karst for the species mentioned in Sánchez-Sánchez & Islebe (2002), but without success. Richards (pers. comm., 2006) has observed that many of the trees that have been blown over by hurricanes, have only lifted an area of soil which is quite shallow, indicating that generally, many of the trees do not have deep root structures.

Beddows (2004) mentions xerophytic characteristics of the vegetation such as waxy leaves and succulent stems/trunks as an indication that the forest has adapted to an environment with limited access to water through the roots and that it is only a limited number of species who has roots that are able to penetrate into the saturated zone.

Exploration of dry and wet caves offers an opportunity to observe the presence of tree roots in the saturated zone. Whether tree roots are able to penetrate into cave systems depends highly on the limestone strata above and the forest type (Coke, pers. comm., 2006). When tree roots are seen in caves, they are unevenly clustered or scattered. More roots are generally encountered in shallow parts of a cave, whereas at larger depths the roots are isolated, since only the roots of larger trees are able to reach this depth (Coke, pers. comm., 2006).

The presence of trees that penetrate into caves can be observed especially in and around cenotes, where ficus trees (ficus cotinifolia ~ strangler figs) often stretch their roots into the water from the surface. An example of this is seen in Figure 2.26. Ficus seem to have an ability to send roots down a long way to water, i.e. > 5m, both horizontally and vertically (Richards, pers. comm., 2006).



**Figure 2.26**. Ficus tree roots stretching into the Dos Palmas cenote (Photo: Simon Richards).

Generally, in dry caves, roots have been observed penetrating the ceiling strata, reach the cave void, and end up on or penetrating the cave floor at a floor depth of 6 to 8 meters (relative to the survey's 0 datum, i.e. ground surface) (Coke, pers. comm., 2006). Richards (pers. comm., 2006) has observed the following types of roots in dry caves:

- Big, woody "tap roots" from ficus trees descending from the ceiling down to water level, then spreading out.
- Root "bundles", which seem to consist of a number of roots bundled together running down from the ceiling to the water then spreading out - these may have carbonate deposits on them, in which case they are known as "rootsicles".
- Fine "fuzz" roots on the walls.

It is unclear from what plants the "bundles" and "fuzz" roots are, but all types of roots are seen even in fairly deep caves (Richards, pers. comm., 2006). In a study of the occurrence of tree roots in the "H+M Cenote" Richards & Devos (pers.

comm., 2006) measured 24 feet (7.3 m) from the ground surface to the water table, and observed many roots coming out of the rock by the water table and connecting to it. It is believed that plant roots

penetrating to the water table in caves may take place if this is the only way the plant roots can reach water or  $\sim 100\%$  humid air, but the ability to do this of course depends on the plant type.

Figure 2.27 shows examples of roots observed in the Tishik Kuna dry cave, which was visited during the field trip. The cave is situated right on the water table. The amount of roots observed in this cave was very limited, as only 1-2 root balls and a few small individual roots was seen.



**Figure 2.27**. From top left: Entrance to the Tishik Kuna cave to illustrate the surrounding vegetation; Root ball is seen in the right side of the picture; Small individual root along the cave wall; Other example of root ball. Note that part of the root balls are covered in calcite (Coke, pers. comm., 2006).

In underwater caves, large tree roots with a fairly fine structure have been seen to descend several metres into the water (Richards, pers. comm., 2006, Coke, pers. comm., 2006). These are notable in caves near domes, but otherwise they are the exception rather than the rule (Richards, pers. comm., 2006). This may be related to the fact that at domes, the limestone layer is thinner and thus easier for the roots to penetrate, and at domes, there may be airfilled pockets with 100% humidity rather than actual water, and this may be easier for some plants to take up. Beddows (2004) has described the density of root ball phreatophytes in underwater caves as quite low (1 per 80 m<sup>2</sup>), based on observations made in an approximately 1 km long and 20 m wide flooded passage in the Nohoch Nah Chich cave system.

It should be noted that even though not many tree roots are seen in caves compared to the density of trees on the ground it cannot be concluded that the roots in general do not reach the saturated zone, as caves are usually located several metres below the water table.

However, a study on the impact of water, soil and nutrients of growth on forest vegetation in the northern part of the Yucatan Peninsula concluded that with a depth of the groundwater table of 8 m below ground level at the study location, only deep-rooting species such as trees with a tap root at an adult stage were able to penetrate into the saturated zone (Reuter, 2006). For comparison Beddows (2004) estimates the thickness of the vadose zone to be 2-10 m close to the coast but 20-50 m further inland, which means that especially inland it will be very difficult for the normal vegetation to reach the saturated zone.

It is therefore expected that direct water uptake by plants from the saturated zone may perhaps occur in the areas closer to the coast, where the depth from the ground surface to the water table is lower. However, in the inland areas it is not expected to be significant. A special case is the vegetation in the extensive wetland areas, which is rooted in geology saturated with groundwater, and thus takes up water directly from the saturated zone. Direct uptake of water from the saturated zone by plants in the model area can therefore not be disregarded in the areas where the unsaturated zone is relatively thin. It should therefore be taken into account in future analysis of evapotranspiration in the model area. However, it is also clear that this is an area that needs further studies, since little is known and most information in this chapter is based solely on personal communications.

# 2.2.8 Main Ecosystems

The model area has a wide variety of ecosystems. First of all, the cenotes constitute their own types of unique aquatic ecosystems. The tropical rainforest is another ecosystem with a large biodiversity. Of the wetland ecosystems in the model area, there are the four overall types: coastal savannas, swamps, marches and mangrove, and in general the land-sea interface along the coast is important for biodiversity. These areas furthermore serve as a buffer zone between land and ocean during storms, thus lowering their impact on the inland areas (Batllori *et al.*, 2000; CESiaK, 2006).

The wetland ecosystems are the host to a wide range of animal and plant species, some of which are endangered, and they are also of importance to fish, molluscs, birds and reptiles in the area (CESiaK, 2006). In Quintana Roo, of land- and wetland-based species, about 500 species of birds are found, and the area is an important bird migratory route. Furthermore, Quintana Roo is the host for 182 species of reptiles and amphibians, more than 1500 plant species, including 117 species of orchids, and more than 100 species of mammals (Meacham, 2003, cited in ASK, 2003b).

Offshore of the model area lies the ecosystems of the Mesoamerican Reef, which is the world's second largest barrier reef. This reef along with the mangrove systems of the Sian Ka'an, are regarded to be some of the world's most productive (TNC, 2006). The reef hosts 85% of Mexico's coralline species and 500 species of fish, and in the area dolphins as well as 4 species of marine turtle can be found (Meacham, 2003, cited in ASK, 2003b).

## 2.2.9 Sian Ka'an Biosphere Reserve

The 5280 km<sup>2</sup> Sian Ka'an area was designated a Biosphere Reserve by the Mexican government in 1986, and in 1987 it was appointed as a UNESCO World Heritage Site (CESiaK, 2006; UNESCO, 2006). It measures about 120 km from north to south, and its location can be seen on Figure 2.1.

Approximately one third of the area is constituted by rainforest, one third by wetlands and the last third is a marine zone, which includes a part of the Mesoamerican Reef (CONANP, 2006). The degree of flooding of the terrestrial areas varies from 20% in the dry season to 75% at the end of the rainy season (CIQRO, 1983, Lopez, 1983 and Consejo *et al.*, 1987, all cited in UNEP WCMC, 2001).

Besides a rich biodiversity the area also has a cultural-historic importance, as 23 Maya archeological sites are registered within the Reserve (UNEP WCMC, 2001). The combination of nature and Maya ruins makes the area a target of tourism activities. Furthermore, the area has a small population; however the number of residents in the reserve is unclear. UNEP WCMC (2001) state the number of inhabitants to be 800, CESiaK (2006) estimate 2000 inhabitants in the area and on the website of Planeta (2006) Sian Ka'an's population is stated to be of more than 5000 people. No data on where these numbers come from or what years they cover have been given in these references. These inhabitants of the Reserve primarily reside near the coast, and mainly make a living by lobster fishing and agriculture, but tourism also generates an income for some, and a hotel and small cabins catering for tourists are found in Sian Ka'an (CESiaK, 2006; UNEP WCMC, 2001; Planeta, 2006). In 2000 36000 tourists visited Sian Ka'an and the number is expected to rise (CESiaK, 2006).

# 2.2.10 Anthropogenic Use

The ancient Maya civilization occupied the Yucatan Peninsula for about two millennia until its collapse in the ninth century (Curtis, 1998; Folan *et al.*, 2000). Maya descendants have continued to inhabit the region until today, but population numbers are now markedly lower than when the Maya civilization peaked, despite a significant immigration facilitated population growth since the 1970's (Folan *et al.*, 2000).

The state of Quintana Roo, in which the model area is located, is one of Mexico's least populated states. However, the rate of population is rapidly increasing. From 1995 to 2006 the number of inhabitants increased by 61%, from ~703,500 people to ~1,135,500 people. The increase was 24% from 1995-2000, and 30% from 2000-2006 (INEGI, 2006). Approximately half of the population resides in the Benito Juárez municipality where the main tourist centre of Cancún is situated, and Quintana Roo is described as one of the most urbanized states of Mexico (INEGI, 2006; Alcocer *et al.*, 1998).

In Quintana Roo, only Chetumal close to the Belize border and Cancún in the north, have more than 50,000 inhabitants. The population density in 2000 was 11 to 50 people per km<sup>2</sup> in the municipalities of Orthón P. Blanco and Solidaridad, while the municipalities of Felipe Carrillo Puerto and José María Morelos had a population density of 0-10 people per km<sup>2</sup> (INEGI, 2006).

The dominant anthropogenic land use in the region is agriculture (Pacheco *et al.*, 2001). After the rapid declines in population resulting from the Maya civilization collapse and later the European colonization,

large-scale agriculture was replaced by small-scale milpa agriculture<sup>4</sup>, which remains the main source of subsistence of a high number of small settlements all over the Peninsula (Faust & Bilborrows, 2000). However, during the past 15-20 years the region has experienced a change in agricultural practices. The introduction of government and commercial farms as well as fertilizers and pesticides has resulted in intensified agriculture and land use changes (Faust & Bilborrows, 2000). Although agriculture only covers a relatively small part of the area, around 38% of the population within the model area work in this sector (Batllori *et al.*, 2000). However, poverty is great, especially in the rural areas, one reason being decreasing yield of traditional agriculture (Eastmond *et al.*, 2000). In the southern part of the model area, there is also a limited industrial sector which processes wood and sugarcane (Batllori *et al.*, 2000).

Development of tourism in Cancún and on the Riviera Maya began in 1970 as part of a national tourist development plan, and as a result tourism and related activities have replaced agriculture as the main source of income for the region, and has resulted in a substantial population growth and pressure on the nearby ecosystems (Battlori *et al.*, 2000; Eastmond *et al.*, 2000).

This importance of tourism is reflected by the fact that 48% of the population in the northern part of Quintana Roo is employed in the service sector, where most of this is in related to tourism. Furthermore, it is discerned from the fact that an estimated 30% of the foreign currency generated from tourism in the whole of Mexico is generated in the north of Quintana Roo (Gobierno del Estado de Quintana Roo, 1993, cited in Battlori *et al.*, 2000).

Signs of anthropogenic activities can also be found in the groundwater, due to the high permeability of the aquifer. Sources of contamination are agricultural chemicals, such as nutrients and pesticides as well as faeces of domestic animals, which can enter directly through cracks in the surface (ASK, 2003b). Also the local disposal of wastewater constitutes a growing threat of the groundwater.

In general, the state of Quintana Roo has insufficient wastewater treatment, as the coverage of wastewater treatment is generally below 50% and in 2 of 8 municipalities even non-existent (CNA, 2003, cited in ASK, 2003b; ASK, 2003b). Wastewater is often disposed off directly into the aquifer or through septic tanks which typically have a retention time of only a few hours (ASK, 2003b, Marín *et al.*, 2000). It is not uncommon that wastewater is disposed of in the same cenote system used for water supply, a method which only gives a filtering of the coarse particulate matter (Doehring & Butler, 1974).

The consequence is that the groundwater in large areas is unfit for drinking unless treated beforehand (Faust & Bilborrows, 2000). In addition, the coastal part of the aquifer is generally dominated by saline water and therefore not fit for human consumption (Graniel, 1999).

<sup>&</sup>lt;sup>4</sup> The milpa system of traditional agriculture is based on a system of continuous fallow rotation and a variable mixture of crops adapted to the soil conditions such as e.g. maize, beans and squash (Prieto, 2000).

# 3 Theoretical Background for Electromagnetic Geophysical Methods

Both time-domain and frequency-domain electromagnetic measurements have been part of the field work activities in the present project. In the following the theoretical setting for these methods is provided.

# 3.1 Electrical Resistivity and Conductivity and Electromagnetic Geophysical Methods

Electromagnetic geophysical methods utilize the fact that different geologic media, as well as different types of water in the geological matrix, have different abilities to conduct a current. The terms electrical conductivity ( $\sigma$  [Siemens/m]), which is the ability to conduct an electric current, and electrical resistivity ( $\rho$  [Ohm-m]), which is a measure of how a material opposes the flow of an electric current, are used to describe this. Electrical resistivity is the inverse of the electrical conductivity.

The resistivity of limestone can be from 50 Ohm-m to  $10^7$  Ohm-m, whereas the resistivity for freshwater is generally in the interval of 20-100 Ohm-m and the resistivity of saline waters is mainly between 0.15 and 0.5 Ohm-m (Telford *et al.*, 1990).

In resistive media such as limestone, a current will mainly be conducted in the electrolyte contained in the pores. Archie's Law expresses the effective resistivity of a media ( $\rho$ ), as depending on the porosity ( $\varphi$ ), the water filled fraction of the pore space (S) and the resistivity of the water ( $\rho_w$ ) (Telford *et al.*, 1990):

$$\rho = a\phi^{-m}S^{-n}\rho_w \tag{Eq. 3.1}$$

where *a*, *m* and *n* are constants ( $0.5 \le a \le 2.5$ ,  $1.3 \le m \le 2.5$  and  $n \approx 2$ ). Archie's Law thereby states that resistivity is controlled primarily by the pore water conditions and the resistivity decreases if the porosity or water filled fraction increases. This means that in high-resistive background environments water filled cavities will be visible as low-resistivity areas in a resistivity profile (Telford *et al.*, 1990).

Electromagnetic (EM) geophysical methods work by creating an electromagnetic field where the magnetic field (the primary field) varies with time. According to Maxwell's equations this will induce an electrical current in the environment, e.g. in the ground below the electromagnetic equipment. This current, and its associated electric and magnetic fields (all termed the secondary field) will then be conducted through the ground, and the conductance will depend on the properties of the ground. Electromagnetic methods measure the sum of the primary and the secondary field, and the secondary field thus contains information about the conductivity of the ground (Christiansen *et al.*, 2006).

Besides the signal transmitted from the ground during EM measurements, there will always be various sources of electromagnetic noise. Important sources of noise are atmospheric electricity resulting from flashes of lightning hitting the earth (termed 'spherics'), as well as EM waves from communication equipment (TV, radio, telephones) and power lines (Christiansen *et al.*, 2006; McNeill, 1983). These

sources of noise have to be taken into account, and if possible, compensated for during data collection and processing.

In the following, a few important aspects regarding the transient domain electromagnetic method – TEM – and the frequency domain electromagnetic method – FEM – will be presented. Both methods transmit a periodic current, but in the TEM method, this current is abruptly turned off before measurement takes place. This means that the primary field is not there when measurements are made. In the FEM method the current is continuous and sinusoidal, and measurements thus contain both the primary and the secondary field (McNeill, 1994).

# 3.2 Transient Domain Electromagnetic Method – TEM

The principle of the TEM method is to send a current through a large (often square) ungrounded loop placed on the ground. The side length of the loop roughly corresponds to the depth of exploration (McNeill, 1994), and the frequency may depend on the depth of exploration wanted. However, mostly, different repetition frequencies are used at the same location. In ground-based TEM the current waveform is mostly square, as shown in Figure 3.1 (Christiansen *et al.*, 2006). The current is abruptly turned off, and this causes a change in the magnetic field and therefore induces a voltage (electromotoric force) in conducting material nearby, e.g. the ground, as described in Faraday's Law (McNeill, 1980a). As the transmitter current is switched off, the receiver measures the rate of change in voltage  $[nV/m^2/s]$  induced in the coil by the secondary magnetic field created in the ground, i.e. measures dB/dt. The measurement is conducted in time intervals ("gates"); usually having logarithmically increasing length of time, because this reduces the impact of noise at late times (Telford *et al.*, 1990; Christiansen *et al.*, 2006). After measurement a new current pulse is transmitted, however the direction of the current shifts each time a pulse is sent, as also seen in Figure 3.1.



**Figure 3.1**. (a) Square current wave form of a TEM transmitter; (b) the electromotoric force induced in the ground according to Faraday's Law; (c) the secondary magnetic field which is measured by the receiver, with measurement time gates indicated. The figure is made on the assumption that the TEM system has a central-loop configuration, with receiver placed in centre of the transmitter loop. Figure from Christiansen *et al.* (2006).

#### 3 - Theoretical Background for Electromagnetic Geophysical Methods

The maximum current density moves outwards and downwards with time. The current transmitted through the ground will therefore gradually become weaker as it progresses through the layers, due to resistance of the geologic layers. Therefore, the signal measured at early times generally stems from the upper geologic layers, while late time signal includes information about the conditions of the lower-lying geology. The diffusion and decay of the current is fast in highly resistive mediums and slow in conductive mediums (Christiansen *et al.*, 2006).

The measured dB/dt-signal is often converted into the so-called "late time apparent resistivity", because this function normalizes the data so that the order of magnitude of the measured ground resistivity can be seen, although it should be noted that variations in the apparent resistivity curve does not always correspond with changes in geology (Christiansen *et al.*, 2006). Apparent resistivity curves will also be shown in the data treatment of the ProTEM47 results presented in Chapter 4, as this is calculated by the used data treatment software. However, formulas for the late time apparent resistivity may be found in e.g. McNeill (1994) or Christensen *et al.* (2006).

The measured data may be interpreted by fitting the simulated signal from a 1D geological model to the measured data curve. This 1D model is an average geologic model for the area which the loop covers. However, due to the presence of noise, data are always associated with some uncertainty, which can be quantified to a certain extent. Thus, fitting of a model is done within the uncertainty of the measured signal, and therefore, different models may be fit to describe a measured data curve. This equivalence is inherent to geophysical methods and cannot be avoided (McNeill, 1994). However, it can be dealt with by e.g. applying a priori knowledge on the geology for the data interpretation and/or by choosing the simplest model found which has a reasonable fit (principle of parsimony). In addition, data uncertainty can be reduced by improving the signal-to-noise ratio of the measured data. This is e.g. done in the data collection, when several individual measured signal decays of a single frequency channel are measured and averaged over a certain integration time (process also known as "stacking") (Geonics, 2006a). In addition, the signal-to-noise ratio can be improved by increasing the transmitter moment [Amp·m<sup>2</sup>], which is given by the current transmitted through the coil multiplied by the number of turns in the coil, multiplied by the area of the coil (McNeill, 1980a). Thus, by either increasing the current or the loop size of a TEM system, the signal-to-noise ratio can be improved and also the depth of exploration increases.

# 3.3 Frequency Domain Electromagnetic Method – FEM

In the FEM method, a continuous alternating current is sent through a transmitter loop. The alternating current generates a time-varying magnetic field, which again by the principle of induction generates smaller electrical currents in the subsurface. These currents then generate a secondary magnetic field, which is transmitted downwards through the ground (McNeill, 1980b). Because the primary field is not shut off, the receiver measures both the primary and secondary field. However, when the distance between the receiver and the transmitter is much lower than the "skin depth" <sup>5</sup> of the electromagnetic signal used, the ratio between the secondary and primary magnetic field measured at the receiver becomes proportional to the conductivity of the ground. This principle is utilized in the FEM methods so that the measured signal can be converted into an average apparent conductivity of the ground, which can be read directly from the instrument. Apparent electrical conductivity is an average of the true conductivity value of all materials within the sampled volume (McNeill, 1980b).

<sup>&</sup>lt;sup>5</sup> Skin depth: The distance that a plane EM wave of a certain frequency can travel in a homogeneous half-space of a certain resistivity, until its amplitude is reduced to 1/e of its amplitude at the surface (McNeill, 1980b).

FEM methods only measure one particular frequency, and this makes it easier to filter noise off. However, coil geometry has to be very accurate, or may otherwise introduce additional noise to FEM measurements and worsen the signal-to-noise ratio (McNeill, 1983, McNeill, 1980a).

The FEM instrument applied in this project is the EM34 developed by Geonics Ltd., Canada. The applied frequency of the current depends on the spacing between the transmitter and receiver coils, which are portable. Table 3.1 displays the frequencies used for different coil spacings.

Table 3.1. Frequencies used at different intercoil spacings for the EM34 instrument (Geonics, 2006b).

Coil spacing (m)	Frequency (kHz)
10	6.4
20	1.6
40	0.4

The EM34 instrument is not capable of giving a detailed resolution of the vertical variations in conductivity of the subsurface. However, it is applicable for *qualitatively* detecting anomalies. The signal may then be interpreted by applying a simple geological model of the underground.

In our study site, using a simple conceptual understanding of the subsurface is applicable for our purposes. Thus the underground can be explained by a 3-layer model, where the upper layer is unsaturated limestone, the middle layer is limestone saturated with freshwater and the lower layer is limestone saturated with saltwater. If a conduit is present at the location, the middle layer is instead interpreted as being a freshwater conduit.

The measured signal can thus be modelled using the following relationships given in McNeill (1980b):

Calculated response of the 3-layered geology, i.e. apparent conductivity,  $\sigma_a$ :

$$\sigma_a = \sigma_1 [1 - R(z_1)] + \sigma_2 [R(z_1) - R(z_2)] + \sigma_3$$
 (Eq. 3.2)

where  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  is the electrical conductivity of the upper, middle and lower geological layer, respectively,  $z_1$  and  $z_2$  is the depth from the surface to the lower level of the upper and the middle layer, respectively, and  $R(z_i)$  is a function which defines the relative contribution of all geologic material below depth z to the apparent conductivity when using the EM34 instrument. R(z) depends on whether the EM34 coils are kept in vertical or horizontal co-planar configuration when measuring. In this project we have only used vertical co-planar, also called horizontal dipole mode, meaning that the coils were placed vertically on the ground surface, and for this configuration the function is defined in the following way:

$$R_H(z) = (4 \cdot z_{norm}^2 + 1)^{1/2} - 2 \cdot z_{norm}$$
(Eq. 3.3)

where  $z_{norm}$  is the depth divided by the spacing between the coils.

Figure 3.2 depicts the conceptual model. The mathematical description of the model has been utilized in the data processing to establish reasonable geologic models of the subsurface beneath the measured transects. This will be presented in Chapter 7.

3 – Theoretical Background for Electromagnetic Geophysical Methods



Figure 3.2. General conceptual model of the subsurface at the field locations.
# AQUIFER STATE

# AQUIFER STATE

The aquifer of the model area consists of a thin freshwater lens floating on top of saline water. The following two chapters will investigate this configuration further. First, the depth to the halocline and its variation with distance from coast will be discussed. Second, the head elevation of the freshwater lens will be treated. In this way, the thickness of the freshwater lens with distance from the coast is analyzed.

# 4 Saltwater/Freshwater Interface Configuration

The freshwater and the underlying saltwater of the aquifer are separated by a halocline – the interface between these two water types. Divers observe the halocline in many of the dived caves, and this interface is generally sharply defined due to density as well as temperature differences, as the saltwater is warmer than the freshwater (Beddows, 2004; Smart *et al.*, 2006). The depth of the halocline increases with distance inland from the coast.

Close to the coast, especially from 0 to 3.5 km from the shore, the halocline is less sharply defined and there is an actual mixing zone of brackish water between the freshwater lens and the underlying saltwater (Beddows, 2004; Coke, pers. comm., 2006). This mixing zone may be from 1 m to > 3 m thick, and is formed by an increased degree of mixing, most likely caused by tidal effects greatly impacting the part of the aquifer closer to the coast (Beddows, 2004).

Beddows (2004) investigated the variation in depth to the halocline with distance from the coast based on measurements in conduit systems, cenotes and boreholes. She found that from 0.4 to 10 km from the coast, a linear relationship with slope -1.45 m/km and a negative intercept describes the depth-variation best ( $R^2$ =0.88, n=33) (Beddows, 2004; Smart *et al.*, 2006). In addition, she found that the halocline has a very steep gradient adjacent to the coast (0-0.4 km from the coast), so that the linear relationship does not fit here (Beddows, 2004).

It is surprising that a linear relationship describes the depth to the halocline well in the first  $\sim 10$  km from the coast, since typically the groundwater under an island (or, in this case, a peninsula) would be in the form of a lens-shaped freshwater body floating on top of the saltwater, thus resulting in a curving interface (e.g. Vacher, 1978; Wallis *et al.*, 1991). This follows from application of the Ghyben-Herzberg principle combined with Darcy's Law, the continuity equation and the Dupuit assumptions of horizontal flow (Vacher, 1988). However, Beddows' linear relationship does not seem valid for describing depth to the halocline at sites significantly further inland than 10 km from the coast as can be seen on inland data from Beddows (2004) and references cited herein.

In the present chapter, geophysical ProTEM47 measurements carried out in the model area to detect the depth to the halocline will be presented. Subsequently, these results as well as field data collected by Beddows (2004) and data found in other references, will be compared with an analytical hydrological model that uses the Ghyben-Herzberg principle to predict the depth to the halocline as a function of the distance from the coast. The data results will also be compared with the linear relationship found by Beddows (2004).

It should be noted that according to findings by Beddows (2004) and descriptions by cave divers in the area, the location of the halocline is practically constant in time, and furthermore its variation in depth with distance from the coast is generally similar in all the explored cave systems, except the Caapechen system as mentioned in Chapter 2 (Beddows, 2004; Coke, pers. comm., 2006; Schmittner, pers. comm., 2006). Only observations after extreme rainfall events such as hurricanes, give a more blurred picture. Le Maillot observed the depth to the halocline at several different conduit sites and cenotes to be unchanged about one month after Hurricane Wilma discharged ~1070 mm of rain in 42 hrs on 22 October 2005 (NCDC, 2006a), but at two sites, the halocline was located respectively 1.9 m shallower and 1.2 m

deeper than normally (Le Maillot, pers. comm. 2006). Escolero *et al.* (2005) studied the halocline in the Merida area of the Yucatan state and their findings suggested that the halocline may behave like a spring after an extreme rain event and move up and down until the energy provided to the system by the extreme amount of extra rain has dissipated.

Variations in depth of the halocline with time were found by Beddows (2004) to be smallest at the bottom of the mixing zone, and to mainly consist of short-term variations, while in a long-term perspective, depths were generally unchanged. In addition, she found that the rain recharging the aquifer in the rainy season generally had little effect on the depth to the halocline (Beddows, 2004). For these reasons, in the modelling efforts presented below it seems reasonable to assume a generally static depth to the halocline, which thus only varies with the distance from coast.

# 4.1 Measurement of Depth to the Halocline

Measurements have been made in the model area with the time-domain electromagnetic equipment ProTEM47D (Geonics, 2006a). The main purpose of using this equipment was to map the depth to halocline at various distances from the coast. Transient electromagnetic (TEM) methods are especially suited for detecting the depth to the halocline since they are particularly sensitive to highly conductive layers. This is because current diffuses slowly in these layers, so these layers contain more current and the signal therefore can be more easily detected (Christensen *et al.*, 2006). The ProTEM47 instrument induces a current in the underground via an ungrounded loop, and measures the rate of change of the secondary magnetic field (dB/dt) which is created in the ground as a result and which is measured with a receiver coil. Data are usually interpreted in terms of a 1-dimensional layered earth model. Model parameters (thicknesses and conductivities of layers) are adjusted to yield optimal correspondence between measured and modelled data. This inversion process yields an average geological model of the ground above which the sounding has been made. The saline part of the aquifer will then show in the geologic model as a lower-lying high-conductivity layer, and from this the depth to the halocline can be interpreted.

Below, the ProTEM47 measurements made will be described. Details will also be given on the data treatment, the quality of the data and the results of the data inversion so that the reader is able to assess the reliability of the obtained depths to the halocline.

The mechanisms of the instrument and of data treatment have been further described in Chapter 3 and in Appendix E.

## 4.1.1 ProTEM47 Locations and Measurements

ProTEM47 soundings were carried out in cooperation with Mario Rebolledo-Vieyra and Centro de Investigación Científica de Yucatán (CICY).

The ProTEM47 soundings were carried out along a profile perpendicular to the coast. Table 4.1 displays the details of each location and Figure 4.1 shows the locations on a map. At all sites, measurements were made with 3 different repetition frequencies: 285 Hz (ultra high moment, UH), 75 Hz (very high

moment, VH) and 30 Hz (high moment, HI). These frequencies are chosen to be sub-harmonies of the power line frequency (60 Hz) in order to minimize noise (McNeill, 1980a). For the ultra high moment, 1 Ampere current was used, while for the two other channels 3 Ampere current was used. The high current is used in order to obtain a better signal-to-noise ratio, however cannot be used for the 285 Hz measurements, as the signal will then be oversaturated (HGG, 2002). For each frequency and each setting at each location, about 6 different soundings were made. Generally, large loop sizes were used in order to improve the signal-to-noise ratio further.

Table 4.1. Details of the Horizontal Soundings.								
Name of locality	Code	UTM Zone 16N WGS84 Coordinates		Loop size [m x m]	Turn- off time	Distance from coast	SRTM elevation [mamsl]	GPS elevation [mamsl]
		X	у		[µs]	[KIII]		
San Antonio May	Tulum 01	431910	2258837	100 x 100	5	32.5	25	30
San Francisco Uh May	Tulum 04	440313	2250749	100 x 100	5	21	14	12
Burned plot	Tulum 05	444636	2245363	40 x 40	2.5	14.5	26	27
Tulum Technical School	Tulum 08	451329	2235185	100 x 100	5	3.5	6	4

**Table 4.1.** Details of the ProTEM47 soundings.



Figure 4.1. Locations of the ProTEM47 soundings (red stars).

All locations except the burned plot were football fields located at the outskirts of the villages. These sites were well suited for ProTEM47 measurements, since they were clear of vegetation and had the sufficient size for the loop. Pictures of the survey locations can be seen in Appendix E.

The burned plot was a location with trees and vegetation, where parts of the vegetation had been cleared by burning. The plot had many karstic holes visible on the ground surface, with few meters separation. Most were rather shallow, not intersecting the water table, and with diameters less than 0.5 m. However, a couple of larger karstic openings were found in the area, where the water table was visible and the diameter was  $\sim 1$  m. The ProTEM47 soundings were made about 80 m from these. Due to the presence of vegetation it was necessary to choose a smaller loop size for this location. The turn-off time was then adjusted accordingly, as described in Geonics (2006a).

At all locations except Tulum Technical School, there were no power lines visible in the area. At the Tulum Technical School, there were powerlines 20-50 meters from the area of measurement, but based on the results seen in the field it was obvious that these power lines did not cause noticeable interference or noise in the signal.

At all locations the background noise level was recorded prior to making the actual soundings. This was done by making a sounding at each of the channel frequencies with the transmitter switched off. At all locations the background noise level ranged from  $2 \cdot 10^{-10}$  to  $2 \cdot 10^{-5}$  V·m<sup>-2</sup>·s<sup>-1</sup>, meaning that generally only the very last gates of Channel 3 would intersect with the noise level. Furthermore, at some locations extra noise measurements had been recorded at Channel 2 and 3 (VH and HI).

#### 4.1.2 Data Treatment, Inversion and Results

The sounding data were treated using the SiTEM software, Version 2.1.10.81, the SEMDI software, Version 2.1.10.81, and the underlying inversion code em1dinv, Version 2.13. All have been developed by the HydroGeophysics Group, Department of Earth Sciences, University of Aarhus, Denmark. SiTEM was used for processing of the data, while the SEMDI interface for em1dinv was used for data inversion.

Below, the necessary set-up for reading the data files properly prior to the data treatment in SiTEM is described. Subsequently, data treatment and results of the inversions are presented for each measurement site separately. Loading of data from the instrument and treatment of the raw data files is described in Appendix E.

## 4.1.2.1 Settings for Reading and Treating the Data

In order to read and treat the data correctly in SiTEM, various settings had to be specified.

The transmitter waveform was specified with the respective repetition frequencies and an integration time of 8 seconds, which was used during the soundings. The turn-on of the current was modeled as a linear function. However, the turn-on time has to be input into SiTEM as a so-called exponential decay constant of the turn-on ramp, and other settings are then applied in the geometry file to make sure it is modeled as a linear function. The exponential decay constant of the turn-on ramp ( $\tau$ ) was calculated with the following formula from SiTEM (2001):

$$t_{ProTEM47} = \ln (0.5) / (current rise time in seconds)$$
(Eq. 4.1)

The current rise time depends on the type of copper wire used in the transmitter loop, as well as the loop size. We used the type AWG #10, and the current rise time could then be read from Geonics (2006a). For the 100 m x 100 m loop, current rise time was found to be  $3.25 \cdot 10^{-4}$  s, yielding  $\tau_{100x100} = 2.1238 \cdot 10^{-3}$  s<sup>-1</sup>. For the 40 m x 40 m loop, current rise time was found to be  $1.70 \cdot 10^{-4}$  s, yielding  $\tau_{40x40} = 4.0773 \cdot 10^{-3}$  s<sup>-1</sup>.

Turn-off was also modeled as a linear function using the turn-off time shown in Table 4.1.

Table 4.2 displays the gate center times used for each channel, as specified in Geonics (2006a). Also the amplification factors used are displayed. When using certain settings in the ProTEM47 instrument, the instrument reduces the data with reduction factors (Geonics, no year), but it is then supposed to be automatically corrected in the data file (Auken, pers. comm., 2006). This was not the case for the instrument used. Therefore, the raw data display a step-wise shape if plotted without modification (example shown in Figure 4.2). To make up for that effect, the mentioned amplification factors have to be assigned to the readings at the respective gates.

 Table 4.2. Gate center times and amplification factors used.

	285 HZ	75 HZ	30 HZ	
Gate	Time	Time	Time	Amplification
	[µs]	[µs]	[µs]	factor
1	6.813	35.25	88.13	1
2	8.688	42.75	106.9	1
3	11.13	52.50	131.3	1
4	14.19	64.75	161.9	1
5	18.07	80.25	200.6	1
6	23.06	100.3	250.6	4
7	29.44	125.8	314.4	4
8	37.56	158.3	395.6	4
9	47.94	199.8	499.4	4
10	61.13	252.5	631.3	4
11	77.94	319.8	499.4	10
12	99.38	405.5	1014	10
13	126.7	514.8	1287	10
14	166.4	654.3	1636	10
15	206.0	832.3	2081	10
16	262.8	1059	2648	40
17	335.2	1349	3373	40
18	427.7	1719	4297	40
19	545.6	2190	5475	40
20	695.9	2792	6978	40

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**Figure 4.2**. Example of raw data when the amplification factor has not been applied to the gates mentioned in Table 4.2 (left). The step-wise shape of the function is clearly seen. Right: After correction with amplification factors.

Since the gate center times from Geonics are given relative to the end of the turn-off ramp, and SiTEM needs them relative to the beginning of the turn-off ramp, the gate center times were all shifted by adding the length of the turn-off ramp to the gate centre times.

The ProTEM47 receiver filters high-frequency noise away by band-limiting the input signals. In addition, gain amplifiers also act as filters (Effersø *et al.*, 1999; Levy, pers. comm., 2006). Effersø *et al.* (1999) demonstrated that this must be taken into account in the data processing, as inversion may otherwise yield erroneous geological models. Therefore, this is accounted for by applying standard low-pass filters for digital ProTEM47 to the modelled data during the inversion. The details of the used filters are shown in Table 4.3, and they are specified when importing the data into SiTEM.

Channel		Order	Cut-off frequency [KHZ]
UH	1 <sup>st</sup> filter	1	240
	2 <sup>nd</sup> filter	1	620
	3 <sup>rd</sup> filter	2	450
VH	1 <sup>st</sup> filter	1	240
	2 <sup>nd</sup> filter	2	450
	3 <sup>rd</sup> filter	2	450
HI	1 <sup>st</sup> filter	1	370
	2 <sup>nd</sup> filter	1	420
	3 <sup>rd</sup> filter	2	450
-			

**Table 4.3**. Low-pass filters applied to the raw data. Details of the filters are taken from the standard low-pass filters used for digital ProTEM47 shown in the standard geometry-files provided with the SiTEM software.

The central-loop configuration of the measurements with the receiver being centered in the transmitter loop was accounted for in SiTEM's geometry file by setting transmitter and receiver coordinates to (x,y) = (0,0).

#### 4.1.2.2 Data Treatment and Results

In the following, data treatment and results for the first site – Tulum01 (San Antonio May) – will be described in depth. Subsequently, only the results of the inversions of the data from the other locations will be shown. Further details on the data treatment and results of these other locations may be found in Appendix E.

#### Tulum01 (San Antonio May)

#### Data Processing

The data used for the data treatment and analysis of the Tulum01 soundings consisted of:

For UH and VH:

- 6 repetitions of noise measurements (transmitter loop not connected)
- 3 repetitions of noise measurements (transmitter loop connected)
- 3 repetitions of data measurements (Current: 1 Amp for UH, 3 Amp for VH)

For HI:

- 6 repetitions of noise measurements (transmitter loop not connected)
- 6 repetitions of data measurements (Current: 3 Amp)

The unprocessed data are seen in Figure 4.3, both as the measured time derivative of the magnetic field (Figure 4.3a and 4.3b), as the average time derivative of the magnetic field normalized by the transmitter moment (4.3c), and as average apparent resistivity (4.3d). Red colour indicates the UH moment, green the VH moment and blue the HI moment.

On the dB/dt plot of the raw data (Figure 4.3a) the noise recordings are also displayed. The noise recordings are used to assign a standard deviation to the recorded data, and are also used for weeding the raw data for measurements which are too heavily influenced by noise. This is done by first estimating the noise function, which the software does automatically based on user settings, and given the fact that random noise falls off proportionally to  $(time)^{1/2}$  when using the log-gating technique (Christensen *et al.*, 2006). We set the software to estimate the noise function on the basis of our noise measurements. More information on the noise function may be found in SiTEM (2001). The noise function and the raw data are seen on Figure 4.3b.

In addition to estimating noise of data with the noise function, each data point is added a uniform level of uncertainty. Here, it has been chosen to add a uniform standard deviation of 0.05  $[V/(m^2 \cdot s)]$  to each data point.

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**Figure 4.3.** Raw data from Tulum01 (San Antonio May). Red is the data from using the 285 Hz frequency (Channel 1), green is the data from using the 75 Hz frequency (Channel 2) and blue is the data from using the 30 Hz frequency (Channel 3).

Data trimming was now undertaken to eliminate the points which were too strongly influenced by noise. Trimming of the data was made on the Rhoa-plot in order to maintain the correct signal-to-noise ratio, because this ratio is calculated based on the raw data in the dB/dt plot (Auken, pers. comm., 2006). Especially data were trimmed if they were positioned below or near the noise function curve.

In addition, more noise (higher uncertainty) was added to some data points if they were slightly off the expected curve pattern. This is done to give that particular data point less weight in the fitting of the model to the data during the inversion.

For the Tulum01 data, the first 2 gates of the UH channel were deleted, as there seems to be an instrument or measurement error here, because the signal at those gates has a significantly higher apparent resistivity (see Figure 4.3d). In addition, the last 10 gates of the UH channel were deleted, as they were off, and HGG (2002) suggests only using the first 10 gates of the UH segment.

- The last gates of the VH channel were deleted, as they intersected with the noise measurements.

- The first gate of the HI channel was deleted, as it was off the normal curve (very low apparent resistivity here).

- The last gates of the HI channel were deleted, as they intersected with the noise measurements.

5% noise was added to early VH and late UH gates. 10% noise was added to VH and HI gates at places where they did not overlap so well.

The processed data are seen in Figure 4.4.

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a) Processed data - time derivative of the magnetic field with noise function

**b)** Average dB/dt normalized by transmitter moment.



**c)** Average apparent resistivity ('Rhoa-plot').

**Figure 4.4.** Processed data from Tulum01 (San Antonio May). Red is the data from using the 285 Hz frequency (Channel 1), green is the data from using the 75 Hz frequency (Channel 2) and blue is the data from using the 30 Hz frequency (Channel 3).

#### Inversion with SEMDI/em1dinv

The processed data was inverted with SEMDI/em1dinv. The inversion was performed with 2- to 5-layer initial models, which had all parameters free (i.e. resistivities of all layers, depths and thicknesses of layers). The result showed that a 3-layer model fits the data best, as can be seen in the residual plot in Figure 4.5, where a 3-layer model gives marked improvement in residuals compared to the other models. In general, a model is selected when the adding of an extra layer has improved the residuals significantly. Small improvements of residuals due to addition of an extra layer are not accepted due to the wish for as simple a geological model as possible (parsimony). That a 3-layer model is the best is also expected, since the general simple conceptual understanding of geology is that it consists of an upper dry limestone layer, a middle layer of limestone saturated by freshwater, and a lower layer of limestone saturated by saltwater to an 'infinite' depth, as mentioned in Chapter 3.

The 3-layer model of Tulum01 has total residuals of 0.50, which indicates a good fit. The residuals calculated by SEMDI/em1dinv are normalized with the signal-to-noise ratio, so that they consist of the difference between model value and measured value, divided by the standard deviation. A value of 1 thus indicates that the model has been fitted within the standard deviations of the data points (Auken, pers. comm., 2006). Hence, a fit with residuals lower than 1 is indicative of a good fit.



Figure 4.5. Total residuals for models of Tulum01.

The parameters determined for the 3-layer model of Tulum01 are shown in Figure 4.6, along with uncertainties given in percent. The software output is actually standard deviations (STD) given as factors, such that an STD of e.g. 1.08 means an uncertainty of 8%. However, if a parameter is free, its STD is given as 99 (this will be seen for Tulum04 data presented later).

The model of the Tulum01 data determines the depth to the halocline to be 79.3 m below ground level (range: 77.7-80.8 m below ground level). The parameter is very well determined with only an uncertainty of 2%.

The depth of the unsaturated resistive first layer is well determined, within 7%, and is 35.7 m below ground level (33.2-38.2 m below ground level).

The resistivities are also seen in Figure 4.6 and are seen to be well determined for Layer 1 and 2, according to the model, but only determined with 22% uncertainty for Layer 3. Values correspond rather well with values found in the same area by Supper *et al.* (submitted), since Supper *et al.* found values between 175-250 Ohm-m for the upper dry limestone layers in the area, 50-100 Ohm-m for middle layers characterizing freshwater in the aquifer, and values between 4 and 15 Ohm-m for the lower saltwater layer in the aquifer.



**Figure 4.6**. Model parameters, uncertainties and residuals for the 2-layer model of the Tulum01 data set. Left hand panel: Resistivities ( $\rho$ ), thicknesses (left) and depths (right) of unconstrained geologic model as inverted by SEMDI/em1dinv (not to scale). Right hand panel: Log-resistivity versus depth (to scale).

In Figure 4.7 the model is displayed with the processed data so the reader visually can evaluate the model fit.



Figure 4.7. Model fit to processed data. Tulum01.

It was investigated whether the model would be improved if a priori geological information were added. This was attempted by constraining the resistivities of the 3 layers to the values found from geoelectric multielectrode measurements in the area by Supper *et al.* (submitted).

This means that the resistivity for the unsaturated zone of limestone with air-filled karstic cavities was set to 200 Ohm-m with a STD of 1.30, i.e. uncertainty of 30%, resistivity for the freshwater saturated zone of limestone without conduits, was set to 75 Ohm-m with a STD of 1.30, and resistivity for the saltwater zone of limestone without conduits, was set to 8 Ohm-m with a STD of 1.50, i.e. uncertainty of 50%.

This however, was found *not* to improve the 3-layer model, as seen in Figure 4.8, which displays the parameters of that model. Also, a restriction of the model using the resistivities used in the EM34 modelling (presented in Chapter 7) was applied (1000 Ohm-m, 300 Ohm-m and 5 Ohm-m, respectively), but did not improve the model fit either (data may be seen in the DVD-appendix, under the name: Tulum01\_restrictMRV). Therefore, it was chosen not to restrict any model parameters in the following inversions at the other sites.

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Total residuals: 0.74.

Figure 4.8. Model parameters for the 3-layer model of Tulum01 data after inversion using a starting model with resistivities constrained to the values found by Supper *et al.* (submitted).

It was also investigated whether a less severe data trimming would change the parameters of the best-fit model, e.g. the depth to the halocline. Thus, a trial was made, where the last 10 gates of the UH segment were *not* trimmed, and neither were a couple of the last VH gates. However, it was found that this did not significantly change the model (data may be seen in the DVD-appendix under the name: Tulum01\_UHlong). However, it was seen that a proper trimming of the data gave a better fit of the model to the data. This was therefore taken into account in the data processing of the soundings for the other locations.

#### Tulum04 (San Francisco Uh May)

Details of the raw data and the data treatment for Tulum04 may be found in Appendix E. Following unconstrained inversion of the processed data the resulting best geological model may be seen in Figure 4.9, which again is a 3-layer model. The residuals of the model are much lower (0.37) at this location because the Tulum04 data were less noisy.

The depth to the halocline is very well determined to be 60.5 m below ground level with only 1% uncertainty. Other model parameters are seen from Figure 4.9. It is seen that in this case, the resistivity and extent of Layer 1 has standard deviations of 99, which means that these parameters are essentially free. The ProTEM47 data thus cannot help us describe the first layer.

Resistivity of Layer 2 is well determined, within 9%, and is 67 Ohm-m (61-73 Ohm-m), a value roughly a factor 2 larger than found at Tulum01 and equally well determined. Resistivity of layer 3 is well determined (12%) with a value of 1.2 Ohm-m (range: 1.0-1.3 Ohm-m). This is lower than at Tulum01 by a factor 4 but better determined.



**Figure 4.9**. Model parameters, uncertainties and residuals for the 3-layer model of the Tulum04 data set. Left hand panel: Resistivities ( $\rho$ ), thicknesses (left) and depths (right) of unconstrained geologic model as inverted by SEMDI/em1dinv (not to scale). Right hand panel: Log-resistivity versus depth (to scale).

#### Tulum05 (Burned Plot)

The data from Tulum05 have a very high noise level (see raw data in Appendix E, where reasons for the higher noise level are also discussed). Therefore, data trimming for this site had to be more extensive.

After inversion, the resulting model of the data is shown in Figure 4.10. Addition of layers did not improve model fit. Therefore, the 2-layer model must be selected for this location. For this model, residuals are rather high (0.79) owing to the bad quality of the data. According to the model, the halocline is located at 44 m depth, and determined with 3% uncertainty.

The resistivity of Layer 1 must represent an aggregate of both unsaturated zone and freshwater lens in limestone. It is well determined (with only 4% uncertainty) but we know that this layer is not homogeneous, but in fact consists of the above mentioned 2 types, as well as air spaces and water filled cavities, since the locality was very karstified, with many small sinkholes.

The resistivity of Layer 2 is not well determined (35% uncertainty). It is modeled to have a value of 0.5 Ohm-m (0.3-0.7 Ohm-m).



**Figure 4.10**. Model parameters, uncertainties and residuals for the 2-layer model of the Tulum05 data set. Left hand panel: Resistivities ( $\rho$ ), thicknesses (left) and depths (right) of unconstrained geologic model as inverted by SEMDI/em1dinv (not to scale). Right hand panel: Log-resistivity versus depth (to scale).

#### Tulum08 (Tulum Technical School)

The data at Tulum08 were very smooth, and therefore only little raw data processing had to be done for this location.

Following inversion, inspection of model residuals clearly shows that a 4-layer model should be chosen for describing the geology at this location (residual plot may be seen in Appendix E). The model fit is good with low residuals of 0.37.

Parameters for the 4-layer model of the Tulum08 data are shown in Figure 4.11. It is seen that the depth to the halocline is also here estimated well – with an uncertainty of only 4%. The depth to the halocline is thus 28.3 m below ground level (27.2-29.4 m below ground level) based on the inversion of the ProTEM47 data.

The resistivity of Layer 1 is lower at this location compared to the values determined by Supper *et al.* (submitted) as well as compared to the value found at Tulum01 for the unsaturated limestone (for the other sites, the parameters of this layer were free, or Layer 1 was a lumped layer representing all layers above the halocline). The difference is roughly a factor 2 between this location and Tulum01 and Supper *et al.*'s values. This is surprising, because the inversion indicates that this low resistivity of 70.6 Ohm-m is rather well determined (6 % uncertainty; range: 66.4-74.8 Ohm-m). Also the resistivity of Layer 2 is lower than expected although this layer's resistivity has a high uncertainty of 32%. In addition, the fourth layer at this site shows a slight increase in resistivity as well. This is also surprising.

No apparent reasons for the lower resistivities and for the presence of a fourth layer with increase in resistivity at this site have been found. Only speculations can be made. If it is not an instrument error (in gain or current settings, for instance), another possibility could be that this location is more karstified. The ProTEM47 averages the actual values found under the 100m x100 m loop to an average value, so detailed resolution and identification of conduits cannot be made with this instrument. However, if conduits and karstic dissolution cavities are found in the unsaturated and saturated zone the results could be interpreted in the following way:

Layer 1: Represents the layer from the ground surface down to a conduit filled with freshwater. The reason why this layer is not believed to only be the unsaturated zone is due to the 19 m thickness found for this layer. The groundwater table cannot be located that deep at a site only 3.5 km from the coast. Rather, it is estimated to be around 5.5 m below the ground surface if using a fitted analytical model which will be presented and discussed in the subsequent sections of this chapter. If Layer 1 thus represents both unsaturated limestone, as well as freshwater in the matrix, this might perhaps explain that we obtain a resistivity lower than the 175-250 Ohm-m found by Supper *et al.* (submitted) and than the ca. 200 Ohm-m found at Tulum01. If, in addition, smaller cavities are also present in the matrix here, this may lower the resistivity further, especially in the water-filled part.

<u>Layer 2:</u> The resistivity of the layer is in the same range as that found by Supper *et al.* (submitted) for conduits filled with freshwater, and could therefore perhaps represent the freshwater part of a conduit system.

<u>Layer 3:</u> Must be saltwater, due to the low resistivity, perhaps also including a mixing layer zone, due to the relative proximity to the coast. If the resistivity of the subsequent layer should be higher than that of Layer 3, as predicted by the model, part of this layer might therefore represent saltwater in the lower part of a conduit. However, all of this layer is not believed to be conduit, if Layer 2 should be conduit too, as conduits rarely span 20 m in height.

Layer 4: Must be saltwater in matrix.

This interpretation is speculative, and is just one suggestion out of many possible alternatives. It is evaluated that no firm conclusions as to the reason for the low resistivities can be drawn at this site based on the ProTEM47 soundings. However, the depth to the saltwater interface predicted by the model is trusted to a high degree, even when the other parts of the model cannot be well explained.





**Figure 4.11**. Model parameters, uncertainties and residuals for the 4-layer model of the Tulum08 data set. Left hand panel: Resistivities ( $\rho$ ), thicknesses (left) and depths (right) of unconstrained geologic model as inverted by SEMDI/em1dinv (not to scale). Right hand panel: Log-resistivity versus depth (to scale).

## 4.1.3 Summary of the ProTEM47 Results

Generally, the ProTEM47 measurements showed the expected geological pattern with a high resistivity upper layer (limestone in the unsaturated zone), a medium resistivity middle layer (freshwater in the limestone aquifer) and a low resistivity lower layer (saline part of the aquifer). Therefore, the results seem very reasonable.

However, the resistivities of Layer 1 and 2 were lower than expected compared to the values found by Supper *et al.* (submitted) at most of the sites. One reason is that the signal measured by ProTEM47 is not resolved to a great detail in the vertical direction, but values are averaged over the layers and over the whole loop area. In addition, it should be noted that ProTEM47 equipment is not able in detail to resolve resistivities larger than 80-100 Ohm-m, and instead thus just displays a generally high value for such media. The reason is that high-resistive layers do not yield a significant response in the ProTEM47 equipment, since current is transported rapidly through high-resistive layers, and signal decays rapidly here, which yields limited system sensitivity to high-resistive layers (Christensen *et al.*, 2006).

Table 4.4 displays the results of the depth to the halocline from the ProTEM47 measurements. As expected, the depths to the halocline generally increase inland. In the following section, these depths will be compared with the other data on the depths to the halocline, and to an analytical model describing this.

<u>1</u>			0
Name of locality	Code	Distance from coast [km]	Depth to halocline from ProTEM47 data [m.above surface]
San Antonio May	Tulum01	32.5	-79 (range: -78 to -81)
San Francisco Uh May	Tulum04	21	-61 (range: -60 to -61)
Burned plot	Tulum05	14.5	-44 (range: -43 to -45)
Tulum Technical School	Tulum08	3.5	-28 (range: -27 to -29)

Table 4.4. Depths to the halocline as found by the ProTEM47 soundings.

#### 4.2 Analytical Modelling of the Depth to the Halocline

The Ghyben-Herzberg relationship describes the position of a halocline if this interface is sharp and the two water bodies are in steady state conditions. It states that the pressure of the saltwater on one side of the interface equals the pressure of the freshwater lens on the other side of the interface:

$$\rho_s \cdot z_i = \rho_f(h_f + z_i) \tag{Eq. 4.2}$$

where  $\rho_s$  and  $\rho_f$  are the densities of saltwater and freshwater [M/L<sup>3</sup>], respectively,  $z_i$  is the depth to the halocline from the sea level [L] and  $h_f$  is the head of the freshwater lens relative to sea level [L]. Typical values of seawater and freshwater densities are 1025 kg/m<sup>3</sup> and 1000 kg/m<sup>3</sup>, respectively (e.g. The Physics Factbook, 2002). This yields:

$$z_i = 40 \cdot h_f \tag{Eq. 4.3}$$

This relationship may now be inserted into the Darcy's Law describing water flow in a porous medium. Details on this derivation may be found in Appendix F. Here, only the main points will be given. Assuming steady state conditions, constant recharge rate (r) and hydraulic conductivity (K), and assuming that the aquifer thickness (d) is simply described as  $d = h_f - z_s$ , where  $z_s = -z_i$ , we get the governing equation:

$$-\frac{41K}{2}\frac{d}{dx}h_{f}^{2} = rx$$
 (Eq. 4.4)

As the model will consider flow in the x-direction from a water divide located at x = 0, towards the coast located at x = L, one can apply the boundary condition  $h_f^2(L) = 0$ , since there will be no freshwater head ( $h_f$  = sea level) at the coast. This yields the following solution:

$$h_f = \sqrt{\frac{r}{41K}} (L^2 - x^2)$$
 (Eq. 4.5)

which may be inserted into Eq. 4.3 to yield the (positive) depth to the halocline.

Eq. 4.5 and Eq. 4.3 combined is thus a simple analytical model for describing the freshwater head and the depth of the halocline with distance from coast. This simple model is now fitted to available data on the

depth to the halocline at different sites to give a first estimate of the parameter values of the model, although it is known that in reality neither K or r are constant in the model area. Fitting of such an analytical model was also done by Beddows (2004) with almost the same model, except she included an outflow face at the coast, which means that aquifer thickness is not zero at the coast but has a certain thickness. Nevertheless, the fitting of the above-mentioned analytical model will be repeated here, because we will include the four depths to the halocline found by our ProTEM47 measurements, as well as data from six other locations found in the literature. These additional data give a larger spread to the data points, especially in the area 0-10 km from the coast as seen from Figure 4.12(a). Details of the data and the references for them are listed in in Appendix G. However, it must be noted that we did not obtain the raw data from Beddows (2004) within the time frame of this project, and therefore, her data were read from figures and tables in her publication. This gives an uncertainty to the data of estimated up to 1 m in the vertical direction and up to 1 km in the coastal direction compared to her original data.

In the fitting of the model, the length from the water divide to the coast, L, equal to the flow path length, is assumed to be 100 km. This is based on measurements on a map of the distance from the coast to the assumed water divide. This length of course varies with the location in the model area, as clearly seen from our model outline. Since most data are from the Tulum area, the length L should be from about 50 km to about 120 km according to the map. Further south in the model area L may be up to 140 km. It has been chosen to use an L equal to 100 km, since this seems to give a reasonable shape to the curve of the halocline.

The fitting of the model depends on which data points are given weight in the fitting procedure. Our analytical model has been fitted with special focus on the ProTEM47 data and the data >10 km from the coast, since the best fit from the 0-10 km distance was already found by Beddows (2004). The fitting has been done by minimizing the root mean square error (RMSE). The best fit of the analytical model gave a RMSE of 5.5 m for these data points. A comparison of the RMSE of the best fitted analytical model and Beddows' (2004) linear model is seen in Table 4.5. As seen, the linear model by Beddows (2004) describes the data from 0-10 km best, while our best fitted analytical model is better at describing the inland data.

**Table 4.5**. Root mean square error (RMSE) between observed data and fitted models. The fit arising from including different portions of the data is shown, and the fitted analytical model is compared to the fit of the linear model found by Beddows (2004). Bold text highlights the model which describes the particular data best, due to a lower RMSE. The data option highlighted in bold is the one the analytical model has been fitted against.

Fitted analytical model,	Beddows' (2004)
r= 15%, K=75000 m/d	linear model
5.6 m	10.4 m
4.6 m	1.5 m
6.8 m	15.6 m
5.5 m	19.6 m
5.7 m	3.9 m
7.8 m	19.8 m
4.7 m	3.5 m
	Fitted analytical model, r= 15%, K=75000 m/d 5.6 m 4.6 m 6.8 m 5.5 m 5.7 m 5.7 m 7.8 m 4.7 m

<sup>1)</sup> Excluding the data from the burned plot, since it is regarded as an outlier.

Our best fit of the analytical model to the halocline data is seen from Figure 4.12 (a). Visually it is also easy to see that the analytical model and the Ghyben-Herzberg principle seems to describe the (relatively few) inland data points rather well. In fitting the model there are two unknown variables that have to be determined at the same time, namely the r and the K. In order to limit the possibilities, the r was kept at 15%, 30%, 45% and 60% of mean annual precipitation (~1200 mm/year), and K was fitted accordingly. These different recharges represent the possible span which is thought to be realistic for this unknown parameter of the model area. The shown fit was obtained using the r- and K-value couples displayed in Table 4.6. From this table it is seen that the order of magnitude of the found Ks seems reasonable compared to literature values (see Figure 2.8). The table also clearly shows that there is a direct correlation between r and K so that if r is doubled also K must be doubled. This is a direct consequence of Eq. 4.5.

**Table 4.6**. Recharge and hydraulic conductivity values found for the analytical model with L = 100 km fitted to the available halocline data.

Recharge $(r)$	Hydraulic conductivity $(K)$
15% of mean annual precipitation $\sim$ 0.0005 m/d	37 500 m/d = 0.4 m/s
30% of mean annual precipitation ~ 0.001 m/d	75 000 m/d = 0.9 m/s
45% of mean annual precipitation ~ 0.0015 m/d	112 500 m/d = 1.3 m/s
60% of mean annual precipitation ~ 0.002 m/d	150 000 m/d = 1.7 m/s



**Figure 4.12**. **a)** Halocline data plotted according to the *source* of the data. Red line is our fitted analytical model. **b)** Halocline data plotted according to the *type* of the data. Red line is our fitted analytical model, purple dashed line is the linear model found by Beddows (2004) to best describe the conduit data from 0-10 km from the coast. Halocline data is from the following sources: Beddows (2004; A is data read from figures on p. 121, B is data read from individual graphs and tables in her report, p. 68-78), Buckley (1984), Iliffe (2003), Socki (1984) (all three cited in Beddows, 2004), JICA (2004), CNA (2001) (data from these two sources shown as "Other sources" in Figure **a)** ), our ProTEM47 measurements.

Figure 4.12(b) is a plot of the data according to the *type* of location the data stems from. Also, the Beddows (2004)'s linear model is plotted. Visually it is again easy to see that this linear fit is especially good from 0-10 km from the coast, and is coincident with being data from *conduits*. The reason for the halocline to be located lower than expected is probably that highly conductive sequences of an aquifer located below the sea level, such as conduits, reduces the thickness of the freshwater lens, as also found by e.g. Wallis *et al.* (1991). The numerical simulations of Wicks & Herman (1995) also illustrated this, since they showed that the saltwater/freshwater mixing zone will move towards the location of high permeability and porosity areas ("conduits") located above the halocline, especially if these "conduits" are located close to the coast. They attributed this to the high-permeability zone transporting more freshwater, and thereby reducing the freshwater head below the conduit causing a consequently more shallow position of the halocline and an upward flow of the underlying saline water. Upward flow of the underlying saltwater was also suggested by Moore *et al.* (1992) to be the case at a site on the eastern coast of the Yucatan Peninsula based on data collected at the site (9 km south of Playa del Carmen).

Beddows (2004) also explains her findings with this argument. In addition, the linear trend of the halocline near the coast is explained by Beddows (2004) to be caused by numerous restrictions of conduit flow due to local lowering of the conduit ceiling below the mixing zone, which forces part of the freshwater to move through the matrix instead of the conduit. This would cause a build-up of freshwater head in the upstream part of the restriction, and thus cause lower groundwater heads after the restriction, and hence a lower depth to the halocline, following Eq. 4.3.

The depths to the halocline thus seems to be able to be modelled best by a linear model, as found by Beddows (2004) in the area with extensive coastal conduit development, approx. 0-10 km from the coast, and by the analytical model based on the Ghyben-Herzberg principle at locations further inland.

For readers who are familiar with Beddows (2004) it should be noted that the fitted analytical model found here is different from the polynomial regressions fitted by Beddows (2004) to the data, as may be seen from Figure 4.13. These polynomial regressions do not seem to model the data well inland, and the fitted analytical model, which has a physical basis, is therefore, not surprisingly, seen to be much better than polynomial regression fits.



**Figure 4.13**. Comparison of the best-fit power regressions found by Beddows (2004) (black dashed and dotted lines) with the fitted analytical model (red line). Beddows (2004) found the  $R^2$  of her power regressions to be 0.64 in describing her data from 0 to 10 km from the coast and 0.96 in describing her data from 0-80 km from the coast.

In Figure 4.14 a close-up of the data points from 0 to 10 km from the coast is displayed together with Beddows (2004)'s linear model, her power regression of the data and our fitted analytical model, to better illustrate the points discussed above and also seen in Figure 4.12(a).



**Figure 4.14**.Close-up of the data points from 0 to 10 km from the coast displayed together with Beddows (2004)'s linear model (purple dashed line), her power regression of the data (black dashed line) and our fitted analytical model (red line).

In Figure 4.15(a) an example of varying r and K is seen in order to show the change in shape and location of the curve when these parameters are varied. One of these model parameters from the fitted analytical

model has been kept constant while the other has been changed. Figure 4.15(b) illustrates the effect on the shape of the curve from choosing a different L than 100 km. An L of 80 km and 120 km has been implemented. These two models have been fitted by varying the K and keeping the recharge constant at 30% as in the fitted analytical model.



Figure 4.15. a) The shift in the location of the curve when r or K is varied. b) The change in the model if L is changed.

The analytical model was also developed to take into consideration a zone with different permeability at the coast. The derivation of this model is shown in Appendix F. However, this was not found to improve the model fit, neither when making the zone extend from the coast 1 km inland nor extend 10 km inland, since these models all had higher RMSE than the fitted analytical model presented above. Therefore, these two-zone models are not treated further here. An example of output of this model can however be found in Appendix F together with RMSE of their fits.

## 4.3 Discussion and Conclusions

The analytical model is useful for getting a first feeling of the area which is being modelled, although this model is based on many simplifying assumptions which are known not to be realistic, such as the hydraulic conductivity being constant in space. The analytical model is useful because it allows for immediate evaluation of the order of magnitude of the important model parameters recharge and K.

The analytical model can be fitted to the available halocline data. The best obtained fit here yielded *K*-values between 0.4 and 1.7 m/s, depending on the level of recharge chosen. The fitted analytical model provides a rather good fit to the inland data of the depth to the halocline. Especially, it was found to describe the data from the ProTEM47 measurements well.

Table 4.7 displays a summary of the findings of the depths to halocline, predicted by the inversion of the ProTEM47 results, and by the fitted analytical model, respectively. The actual measurements with the ProTEM47 equipment are regarded to be more accurate than the depths predicted by the fitted analytical model. However, it is seen that the discrepancy between the model and the measured data is low, only 0 to 4 meters. The ProTEM47 soundings thus confirm the conceptual understanding that the depth to the

halocline increases with distance from coast, and that inland, the depth to the halocline seems to be described well by the Ghyben-Herzberg principle. Moreover, it seems that the fitted analytical model is relatively well calibrated with the actual conditions, and is suitable for explaining the variation in the depth to the halocline with distance from coast in the inland areas.

Only at the burned plot (Tulum05) location the deviations between the two models is high, namely 18 to 20 m. However, the ProTEM47 data from this location were also very noisy, and thus had a bad quality. In many ways this site was different than the others and data from this site may therefore be less trustworthy.

Table 4.7. Comparison of the depth to the halocline obtained from ProTEM47 measurements and the fitted analytical model, respectively.

Name of locality	Code	Distance from coast [km]	Depth of halocline relative to surface, predicted by the fitted analytical model using SRTM elevation [m.above surface]	Depth to halocline from ProTEM47 data [m.above surface]	Discrepancy [m]
San Antonio May	Tulum01	32.5	-78	-79 (range: -78 to -81)	1 (0 to 3)
San Fransisco Uh May	Tulum04	21	-58	-61 (range: -60 to -61)	3 (2 to 3)
Burned plot	Tulum05	14.5	-63	-44 (range: -43 to -45)	19 (18 to 20)
Tulum Technical School	Tulum08	3.5	-25	-28 (range: -27 to -29)	3 (2 to 4)

Based on the available data on the depth to the halocline in the model area, it seems that there may be three different areas with different behaviour of the halocline. From 0 to 0.4 km from the coast, the halocline gradient is extremely steep, as found by Beddows (2004) and this may be explained by a low coastal hydraulic conductivity due to restricted conduit passages. From there and about 10 km inland, the depth to the halocline is lower than predicted by the Ghyben-Herzberg principle, and is best described by a linear model found by Beddows (2004), especially where conduits are known to be abundant. This is caused by the fact that the high permeability of the conduits truncates the depth to the halocline, as described earlier, possibly because they remove freshwater very fast and cause an upward flow of seawater from below the freshwater lens. The linearity may be caused by a series of head losses due to lowering of conduit ceilings below the mixing zone (Beddows, 2004). From ~10 km from the coast and inland, the depth to the halocline seems to be well described by the fact that it is only especially conduits located *close* to the coast which may have a truncating effect on the depth to the halocline (Wicks & Herman, 1995).

# 5 Configuration of Freshwater Heads

This chapter seeks to characterize the variation in freshwater heads with distance inland, as this is the primary parameter that will be used in the calibration of the regional-scale groundwater model.

## 5.1 General State

Due to the low relief of the Yucatan Peninsula and the high hydraulic conductivity of the karst the freshwater lens is relatively flat. Studies of especially the northern part of the peninsula have reported water table elevations to be less than 4 m above sea level, even in the inland parts of Yucatan State about 100 km from the coast (Marín *et al.*, 1990 cited in Gonzalo-Herrera, 2002).

The main part of the recharge for the aquifer is believed to be generated in the hilly, central part of the peninsula, where it produces high groundwater levels and from where hydraulic gradients trend towards the western, northern and eastern coasts (Lesser & Weidie, 1998, cited in Gonzalo-Herrera, 2002). Beddows (2004) measured the regional hydraulic gradient to be  $\sim 58$  mm/km based on a measurement of water table elevation 32.5 km inland from the Caribbean coast, whereas a hydraulic gradient of only 7-10 mm/km was found by Marín *et al.* (1990 cited in Gonzalo-Herrera, 2002) in Yucatan state.

## 5.2 Water Table Variations

The water table varies over a range of temporal scales. Low frequency impacts include seasonal variations such as changes in recharge, sea water density and tropical storms and hurricanes, whereas high frequency variations (days or hours) can be impacts from tides and local scale weather conditions such as waves and barometric pressure tides (Beddows, 2004). The magnitude of these impacts on the water table is investigated further in the following.

Little data is available on the seasonal variations in freshwater heads. Beddows (2004) measured the depth of the mixing zone in four cenotes several times in the period from February 1 2000 to September 11 2002. Beddows (2004) found that the aquifer responds fast to daily or weekly variations in recharge, whereas no significant seasonal variations in the thickness of the freshwater lens were detected. The thickening of the freshwater lens that would be expected to occur during the rainy season could not be confirmed. Instead the freshwater lens was observed to be up to 0.5 m thinner in one of the cenotes in the end of the wet season (November/December), than in the dry season level (Beddows, 2004). An apparent continuous outflow from all the coastal conduit sites throughout the year was also found (Beddows, 2004).

These observations may indicate that the baseflow mainly originates from the interior of the peninsula and that the short term fluctuations in water table elevations observed in cenotes and boreholes are mainly due to sub-seasonal changes such as variations in barometric pressure, extreme rain events, seawater density changes and tides, that predominantly affect the near-coastal zone where the water table is closest to the surface (Beddows, 2004). Another possible explanation of the lack of seasonal variations in the water table height could also be enhanced seawater intrusion during the dry season where

freshwater replenishment via precipitation is lacking and the freshwater lens is thinning (Meacham, 2005; Battlori *et al.*, 2000; Villasuso & Ramos, 2000; Back & Hanshaw, 1970, cited in Pacheco, 2001).

Time-varying head observations in the model area are in short supply. Table 5.1 lists data from 19 CNA monitoring wells on the Riviera Maya (between Cancún and Tulum) aggregated from CNA (2001) and JICA (2004). These data are the most detailed data that it has been possible to find, but unfortunately the data only consists of observations from different times of year and with several years between observations. Consistent time series do not exist.

This of course makes it very difficult to further analyse the nature of daily and seasonal changes in the thickness of the freshwater aquifer in the model area. However, the data can to some extent show the magnitude of the differences in freshwater heads, although it should be noted that since exact observation dates are not available it is not possible to say whether these fluctuations are of daily nature, i.e. due to recent rainfall or whether it is a seasonal change. The largest difference between observations is seen at Zona Agricola, where there is a ~1.5 m range between observations made in November 1994 and August 1995 and observations made in November 2002. For most of the other stations the difference is less than 1 m. There is not a clear pattern in the fluctuations that therefore seems to be very localized.

Location	Mar 1992	Apr 1994	Nov 1994	Aug 1995	Aug 2001	Nov 2001	Nov 2002
Zona Agricola		6.22	5.00	5.00	6.050	6.34	6.54
Leona Vicario					5.905		
Juaréz					5.619		
Santo Domingo	8.72	8.42	8.24	8.72	8.299	8.48	8.89
El Ideal					16.368		
Nuevo X'can		17.26	17.72	18.17	17.860	17.35	17.76
Nuevo Durango					20.093		
Tres Reyes	19.50	20.31	19.43	20.23	20.127	20.54	20.87
Cobá	4.70	4.61	4.43	4.70	4.870		4.53
Artesanians Lool Che					16.930		
Rancho Viejo		10.97	10.80	10.66	10.943	10.89	10.95
Chemuyil Caseta					10.871	10.90	10.92
Chemuyil - 2					9.696		9.76
Chemuyil Tres Reyes	4.75	5.07	5.00	5.02	5.112	5.12	5.13
Uxuxubi - 1	18.83	11.71	11.75	11.84	12.023	12.07	12.06
Akumal - 1					5.107		5.14
Akumal - 2					11.017		11.06
Central Vallarta	4.20	4.42	4.28	4.25	4.253		4.46
Km - 10	5.61	5.80	5.50	5.57	5.362		5.77

**Table 5.1**. Heads data (spot values) relative to mean sea level measured in CNA monitoring wells on the Riviera Maya between March 1992 and November 2002. Data from CNA (2001) and JICA (2004).

George Veni and the Kaua Cave Project monitored the fluctuations in water level in cenote Kiwi Dzonot in the southern part of the state of Yucatán from the beginning of January 2003 to the end of July the same year (Veni, pers. comm., 2006). The data is displayed in Figure 5.1 along with rainfall for the closest climate stations located in Cancún and Mérida, ~175 and ~120 km away, respectively. As the data show, the highest water level recorded was -23.43 m below ground surface on January 3 and the lowest

was -23.78 m on July 25, thus showing an overall decreasing trend in the period, but with three peak observations. The largest difference recorded between two observation days was 0.23 m between April 11 and April 18, but the average weekly variations seem to be limited to a few centimetres. Since no full annual cycle of observations is available it is difficult to make any conclusions on how long time it takes before the impact from a rain event can be observed on the water table, and the precipitation hydrographs offer no obvious explanation to the three peak elevations in the middle of the observation period. Also the geological unit this cenote is located in is not known.

In general it must be assumed that the water table in cenotes react faster to precipitation than the water table in the matrix far from cenotes, as the rain water does not have to penetrate the vadose zone.



■ Cancun Airport precipitation (cm) ■ Merida Airport precipitation (cm) ◆ Depth to water (m)

**Figure 5.1**. Water table variations relative to ground surface in cenote Kiwi Dzonot, located in the southern part of Yucatan State, from January to July 2003, displayed with precipitation hydrographs for the same time period for stations in Cancún and Mérida, respectively (data kindly provided by George Veni, pers. comm., 2006).

#### 5.2.1 Impact of Extreme Rain Events

The Caribbean coast of the Yucatan Peninsula is frequently affected by tropical storms and hurricanes moving through the area. The average frequency is 0.62 storms per year, with the central and southern part of the coast not nearly as affected as the north-eastern cap (Merino Ibarra & Otero Dávalos, 1991, cited in Beddows, 2004). This was also seen from Figure 2.16.

The hurricane Wilma that reached the Yucatan Caribbean coast at Playa del Carmen on 22 October 2005 gave about ~1070 mm of rain in a period of 42 hours (NCDC, 2006a). In connection with the water table

measurements in the model area in April 2006, we asked for information on the impact of Wilma at the visited locations when possible. The general trend was that the water table had been observed to rise approximately 1 m above normal and that it had taken more than one month for the water level to return to normal.

This is in agreement with a study from Yucatan State where a 0.68 m rise in water table was measured after Hurricane Gilbert in 1988; however, here it only took about 5 days for the water table to return to the normal level (Marín *et al.*, 1989; Marín, 1990, cited in Beddows, 2004).

## 5.2.2 Impact of Variations in Barometric Pressure

Another meteorological factor that can impact the elevation of the groundwater table and the configuration of the freshwater lens is the barometric pressure. This is only true for unconfined aquifers, as the intruding saltwater is hydraulically connected to the ocean (Beddows, 2004). The implication of this is an increase in sea level by  $\sim 1$  cm per mbar decrease in barometric pressure, also known as the inverse barometric effect (Chapman & Lindzen, 1970, cited in Beddows, 2004). Changes in atmospheric pressure can cause sea-level changes on the order of up to about 30 cm. This increase in sea level elevation can also entail an elevation of the freshwater lens as reported by Vacher (1978, cited in Beddows, 2004), who found that variations in barometric pressure were drivers for day-to-day fluctuations in water table elevations.

It should be noted that hurricanes and tropical storms are extreme low pressures ( $\sim 900$  mbar). This means that the elevated water table levels observed after this kind of weather systems can partly be caused by the inverse barometric effect.

## 5.2.3 Impact of Tide

Tides are the result of gravitational attraction between the earth and the moon and between the earth and the sun along with inertia and centrifugal forces due to the rotation of the earth (NOS, 2006). The effect of these forces on the points of the earth closest and furthest apart from the moon creates the tidal "bulges" of water (NOS, 2006).

Three kinds of tidal patterns exist. The simplest type of tide is the diurnal tide, which exhibits a regular pattern of one high and one low tide each day. A semidiurnal tidal cycle on the other hand has two high and two low tides of approximately equal size every day. The third type of tide, the mixed semidiurnal tide, has two high and low tides a day but the tides reach different high and low levels. The different types of tides are illustrated in Figure 5.2.

The different shapes of the tidal patterns are a consequence of forces acting on the oceans. Two tidal bulges are created on opposite sides on the Earth; one due to the moons gravitational force and the other due to counterbalancing inertia forces. Because the Earth rotates through two tidal bulges every lunar day, most coastal areas experience two high and two low tides every 24 hours. Differences in tidal frequencies and range occur because of the shape of the ocean basins and coastline (NOS, 2006).



Figure 5.2. Schematic illustrations of the three types of tidal patterns; the diurnal, the semidiurnal and the mixed semidiurnal cycles. From NOS (2006).

The tides also change amplitude on a lower frequency scale. When the sun and moon are aligned, the gravitational forces increase, causing very high and very low tides (spring tides). When the sun and moon are not aligned, the gravitational forces cancel each other out and the difference between high and low tides decrease (neap tides). There are two spring tides and two neap tides in the course of a lunar cycle (NOS, 2006).

Beddows (2004) has analysed tidal data records from the beginning of January 2000 to the end of July 2002 from a location ~ 5 km south of Playa del Carmen. Based on these records the tidal pattern is characterized as "mixed semidiurnal microtides" with a spring tide amplitude of 0.3 m and a neap tide amplitude of 0.05 m. The annual ocean level cycle is described as complex, with two highs and two lows every year, with the annual range in ocean level being 0.6 m. This corresponds very well with the findings of Moore *et al.* (1993), who found a tidal effect of  $\pm$  0.3 m at the coast.

The cave systems on the Caribbean coast of the Yucatan Peninsula are directly connected to the sea and it can thus be expected that the impact of tides will be greater in these cave systems than in the surrounding matrix, as the water can move more freely in the cave systems. According to Beddows (2003) the effect of tide has been observed to be  $\sim 40\%$  of  $\sim 30$  cm semi-diurnal cycle in a cenote 5 km from the coast in the Nohoch Nah Chich cave system. Calculations of lag times with distance inland have showed that the percentage of the coastal tidal amplitude expected 10 km from the coast is  $\sim 16$  for the cave system and  $\sim 8.6$  for the surrounding matrix assuming porous medium conditions (Beddows, 2003).

# 5.3 Analysis of Head Elevation Data

With the current level of knowledge, measured head elevations offers the best opportunity for calibrating the regional-scale hydrological model, which is set up later in this thesis. In the following the quantity and quality of the available head elevation data will be described and evaluated.

## 5.3.1 Sources of Data

Observed head elevation data has been obtained from four different sources –Instituto Nacional de Estadistica Geografia y Informática (INEGI), Comisión Nacional del Agua (CNA), Comisión de Agua Potable y Alcantarillado (CAPA) and own field measurements – and consists of measurements distributed over the entire state of Quintana Roo. It should be strongly emphasized that we believe that

the data that is presented in the following and which has been collected during the field trip by making numerous visits to the largest water institutions in Mexico, is the only groundwater head elevation data that exist for the model area.

The available head data is predominantly cited as elevations below ground level, but to be able to compare the data, elevations relative to mean sea level must be calculated. Surface elevations of the points of observation determined by levelling relative to a government topographical benchmark are only reported for a limited number of records, and therefore elevation data for the reported points of measurement have been derived from the near-global Shuttle Radar Topography Mission (SRTM) digital topographic map. This map has a spatial resolution of 90 m and an absolute vertical accuracy of less than 10 m for 99.4% of the cells (Slater *et al.*, 2006). A linear regression analysis has been made of the heads based on surface elevations from levelling compared to heads based on surface elevations derived from this analysis as well as literature on the accuracy of the SRTM topographical map. From this analysis as well as literature on the accuracy of the SRTM topographical map in areas with dense vegetation (Jet Propulsion Laboratory, 2006) it has been found necessary to subtract 5 m from all derived SRTM elevations to get representative values for the actual ground elevation (see Appendix H).

The head elevations have been measured at different times of the year for the different sources of data, and as mentioned only a few data points include several observations. All data can be seen in the DVD-appendix. Mean values of the data that includes several measurements will be used when possible, but for the remaining part of the data single values are regarded as average values. In the following the head elevation data is analyzed based on distance from the coast. The distances from the coast for each observation point has been measured as the shortest distance to the peninsula outline in ArcView GIS 3.2.

#### 5.3.1.1 INEGI

Hydrogeological maps in paper format of the state of Quintana Roo and the centre of the Yucatan Peninsula, with information on head elevations relative to surface ('nivel estático<sup>6</sup>) measured in cenotes and two types of wells ('pozos' and 'norias', respectively<sup>7</sup>), have been obtained from INEGI (no year).

Figure 5.3 shows the spatial distribution of the observation points as well as the corresponding head elevations relative to mean sea level for the three types of observations as a function of the distance from the coast. Observations located outside Quintana Roo have been omitted from the further analysis, since it is expected that groundwater from these areas discharge into the Gulf of Mexico.

<sup>&</sup>lt;sup>6</sup> Nivel estatico' means static level (i.e. not pumped).

<sup>&</sup>lt;sup>7</sup> The technical difference between 'norias' and 'pozos' is not quite clear. By reference to a Mexican technical dictionary it seems that the 'norias' are a rustic type of well, where buckets are used to extract the water, and 'pozo' refers to a more modern type of well (López, pers. comm., 2006).


**Figure 5.3**. Spatial distribution of the INEGI observations for cenotes (light blue), 'norias' (dark blue) and 'pozos' (red) relative to the model area. The three graphs show the head elevations of the observations relative to mean sea level as a function of the distance from the coast for the three observation types. Note the different scales of the y-axes.

Head elevations range between -4 to 12 masl (cenotes), -7 to 22 masl ('norias') and -25 to 55 masl ('pozos'). The observations are very scattered and fail to follow a clear trend that could indicate the shape of the groundwater surface. This is especially true for the 'pozo' data set, where the range between maximum and minimum values are  $\sim 80$  m, which is believed to be too much taking into consideration that the water table is only expected to reach a few metres above mean sea level in the inland part of the model area. The reason for the apparent low quality of the 'pozo' data set is not known, since no documentation was available for how and when the data was collected. By both visual inspection and by running a 3x3 pixel averaging filter on the SRTM topographic map it has been investigated if the observation points were located in areas where sudden changes in topography and the uncertainty of the position of the point could significantly impact the calculated head elevations, but this was not the case. It has therefore been decided to omit the 'pozo' data for the further analysis of the groundwater surface.

#### 5.3.1.2 CNA and CAPA

This data has been aggregated from different groundwater studies from the Riviera Maya and Costa Maya regions carried out by CNA and CAPA or their consultants (CNA 2001; H20, 2004; JICA, 2004). The spatial distribution of the observation points are shown in Figure 5.4. Only a few of the observations are located in the model area.



**Figure 5.4**. Spatial distribution of the CNA and CAPA observations, levelled observation points (blue) and all observation points (red). The left graph show the head elevations of the observations relative to mean sea level as a function of the distance from the coast for head elevations based on levelled surface elevations. The right graph show all data points with elevations based on levelled surface elevation and for points where this data was not available, then based on the SRTM topographical map (-5 m). Data aggregated from CNA (2001), H<sub>2</sub>0 (2004) and JICA (2004).

Some of the data from these studies have been measured in CNA monitoring wells on the Riviera Maya. The surface elevations of these wells have been levelled to a government topographical benchmark, allowing for accurate calculations of the heads relative to mean sea level. The lower left graph in Figure 5.4 shows the levelled head elevations as a function of distance from coast, ranging from  $\sim 0.5$  masl close to the coast to  $\sim 3.2$  masl 60 km inland, which is in good agreement with expected elevations.

The lower right graph shows the elevation as function of distance from the coast for all the observations compiled from the different studies. The main difference between the two graphs is the observations located within a distance of < 5 km to the coast, and it is seen that they are highly vertically scattered. There could be several reasons for this, such as errors in determining an appropriate surface elevation of the coastal observation points or thickening of the freshwater lens close to the coast.

## 5.3.1.3 Field Measurements

In the period 20 to 25 April 2006 we measured water tables in cenotes, lakes and wells in villages in the central part of Quintana Roo, in an area that is bounded on the north by the road between Cobá and Tulum, and to the south by the road between José Maria Morelos and Limones. The water tables were measured relative to surface with a water level indicator. When measuring in wells the water table has been measured relative to the edge of the well, i.e. approximately 1 m above terrain. Therefore 1 m has been subtracted from the measured number to account for this.

The elevation of the point of measurement was read from a GPS, but according to the considerations on the accuracy of the GPS as presented in Appendix H, it has been decided to base head elevation calculations on the SRTM topographic map elevations instead.

For the purpose of analytical modelling of the surface of the ground water table the lakes and inundated areas have been omitted, since based on measurements of the electrical conductivity of the waters it is assessed that the water is mainly rainwater and that they do not intersect the ground water table. This can be seen from Appendix C. It is thus believed that inland surface water bodies other than cenotes are perched water bodies underlain by low permeable material, e.g. ejecta. Shaw (pers. comm., 2006) expressed the same understanding.



**Figure 5.5**. Spatial distribution of the field observations. The graph show the head elevations of the observations relative to mean sea level as a function of the distance from the coast for head elevations derived from the SRTM topographic map (-5 m).

Figure 5.5 shows the spatial distribution of the observation points and a plot of the observed head elevations as a function of distance to the coast. Apart from a few high observations, the measured head elevations range between -5 and 16 masl. The trend is rather scattered.

### 5.3.2 Thickness of Freshwater Lens

As described in Chapter 4 the Ghyben-Herzberg equation for the shape of the freshwater lens has been fitted to the measured values for the depth to the halocline. A plot of the corresponding groundwater surface (dark blue line) is displayed in Figure 5.6 along with the observed heads. The plot is very scattered but to some extent suggests that the freshwater lens is considerably thicker than predicted by the analytical modelbased on the depth of the halocline. To evaluate the actual thickness of the freshwater lens as predicted by the analytical modelbased on the observed heads the analytical model has been fitted to the observed heads by fixing first the recharge and then the hydraulic conductivity. The best fit when the analytical solution is fitted to the observed head elevation data is indicated with a blue dotted line. Table 5.2 and Table 5.3 list the results of the fit for fixed recharge fractions and for fixed hydraulic conductivities, respectively.



**Figure 5.6**. Plot of all observed head elevations above mean sea level as a function of distance from the coast. The dark blue line is the analytical model fitted to the halocline data. The blue dashed line represents the best fit of the analytical solution to the observed heads.

variable.				
Recharge (r)	Recharge (r)	Hydraulic conductivity (K)	Hydraulic conductivity (K)	Root mean square error
[%]	[m/day]	[m/day]	[m/s]	[m]
15	0.0005	6000	0.07	4.90
30	0.001	11000	0.13	4.90
45	0.0015	17000	0.20	4.90
60	0.002	22000	0.26	4.90

Table 5.2. Results of fit of the analytical solution to observed head data. Recharge fixed, hydraulic conductivity variable.

The hydraulic conductivities listed in Table 5.2 range from 0.07 m/s (15% recharge) to 0.26 m/s (60% recharge). The results of the fitting shows that even a large change in recharge fraction does not have a large influence on the order of magnitude of the hydraulic conductivity, however this also means that even small changes in hydraulic conductivity will have an impact on the water table elevation. The found *K*-values do not correspond well to the assessed regional hydraulic conductivity of K = 105 m/d (~ 1.16 m/s) found by Beddows (2004), but all are in good agreement with the range of hydraulic conductivities reported by literature as presented in Chapter 2. A possible explanation to that the value found by Beddows (2004) appears to be too high could be that it is based on modelling of the near-coastal zone of the southern Riviera Maya, which may be more permeable than the inland areas, due to the extensive conduit development.

variable.					
Hydraulic conductivity ( <i>K</i> )	Hydraulic conductivity ( <i>K</i> )	Recharge (r)	Recharge (r)	Recharge (r)	Root mean square error
		[m/day]	[%]	[mm/year]	
[m/day]	[m/s]				[m]
37500	0.434	0.0035	107	1277	4.90
75000	0.868	0.0065	213	2555	4.90
112500	1.302	0.01	304	3650	4.90
150000	1.736	0.0135	410	4927	4.90

Table 5.3. Results of fit of the analytical solution to observed head data. Hydraulic conductivity fixed, recharge variable.

When attempting to fit the analytical model to observed heads keeping the hydraulic conductivities fixed at the level found best for the halocline data, the resulting recharge fractions are extremely high, all exceeding 100%.

As seen in the previous chapter and the present analysis, the analytical model based on the Ghyben-Herzberg relationship is best fitted to the halocline data and the water table data using widely different K-values. It has been seen that the found K-values are much larger when fitting to the halocline data than when fitting to the water table data. The difference is considered to be significant since it is close to one order of magnitude (0.87 m/s vs. 0.13 m/s for 30% recharge). This could indicate that the analytical model and the assumptions behind it are not able to describe the aquifer well. However, the results from

fitting of the analytical model correspond well with the findings of Moore *et al.* (1992) that the halocline is positioned at a much shallower depth than expected based on the measured freshwater heads, meaning that the freshwater heads are higher than expected. Thus, the *K*-value for the aquifer from the sea level and downwards is higher than from the sea level and upwards to the water table, if this relationship should fit. Conceptually this could make sense, since the relative degree of conduit development and secondary porosity development should be larger in the lower part of the aquifer than in the top couple of meters (cp. typical depths of the cave systems, as described in Chapter 2). The surprising difference in *K*-values from the fitting of the analytical model to halocline and water table data thus seems to correspond with field data and the conceptual understanding of the aquifer.

In addition, it must be kept in mind that the analytical model is founded on many simplifying assumptions which are known not to be true, and therefore a very good agreement cannot be expected. For instance it is known that the geology of the aquifer is highly anisotropic with respect to hydraulic conductivity, for a large part because of the conduit development, but also because the hydraulic conductivities are believed to differ between the geologic units, with lower values for the older, cemented units in the central part of the peninsula and high values for the younger units in the coastal regions (Smart *et al.*, 2004).

The geological conditions also suggest that a perfectly lenticular or symmetrical shape of the freshwater lens is not possible, due to the high anisotropy both in vertical and horizontal direction (as in Vacher, 1988). Vacher (1988) also shows that unequal sea levels on each side of an island can cause asymmetry in the Ghyben-Herzberg lens, as the freshwater lens is skewed so that the flow divide is shifted towards the high sea level side of the island, causing the gradient of the water table on this side to be higher than predicted by the Ghyben-Herzberg principle. Beddows (2004) found indications that the elevation of the sea level is 70 cm higher in the Caribbean Sea than in the Gulf of Mexico.

## 5.3.3 Low Permeability in the Near-Coastal Zone

Beddows (2004) found that the freshwater lens was much thicker than expected in the near-coastal zone (0-0.4 km from the coast). In addition, divers have described that the flow in the caves very close to that coast is parallel to the coast and takes place in caves of relatively smaller diameter (Scmittner, pers. comm., 2006, see also Chapter 2). Thus, it is a possibility that there is a low permeability zone in the near-coastal perimeter.

Dense, low permeability caliche layers in the near-coast zone (< 1 km) have resulted in confined conditions and a build up of a landward pressure head north of Merida on the northern coast of the peninsula (Perry *et al.*, 1989, cited in Beddows, 2004). Similar caliche layers with a vertical extent of up to 1.7 m have been found to separate different geological units in the Pleistocene limestones on the Caribbean coast (Rodriguez, 1982, cited in Beddows, 2004). The caliche layers are potentially acting as hydrogeologic controls, but Beddows (2004) considers it to be unlikely that they are causing confined conditions, since the caliche in this area has been observed to be highly fractured and penetrated by root holes and bioturbation.

To evaluate the possibility of a low permeability layer in the coastal zone of the aquifer the analytical solution with a different boundary condition (see Appendix F) has been fitted to the observed heads. This did not show any apparent difference between the best fit of the analytical solution and best fit of the analytical solution with a low conductivity in the near coastal zone and is therefore not further elaborated

on here. A low conductivity zone along the coast could thus not be verified based on the current data and the 1D analytical model.

## 5.3.4 Correspondance with the Ghyben-Herzberg Relationship

With the low quality of the water table data it is currently not possible to conclude whether the Ghyben-Herzberg relationship is valid or not in the model area. This is here illustrated in two ways.

1) One way of testing if the Ghyben-Herzberg relationship is valid, is by comparing the results of the fitted simple analytical models.

It was seen that, if keeping the recharge equal, the simple analytical models were fitted with different *K*-values to give the best fit to the water tables and to the depth to the halocline, respectively. If taking the relationship between the water tables and the depth to the halocline obtained by these two best-fit models, the ratio between the depth to the halocline and the water tables becomes  $\sim -15$  and not -40 as the Ghyben-Herzberg relationship predicts.

However, as was also seen when the analytical model was fitted to the water table data, these data are so scattered that the difference between the RMSE of the best-fit analytical model and the RMSE of the analytical model using the parameters determined from fitting to the halocline data, is only 0.4 m2 (i.e. RMSE = 4.9 m and RMSE = 5.3 m, respectively, for a recharge of 30%; *K* thus being 11000 m/day and 75000 m/day, respectively). Therefore, it can only be concluded that the water table data are so scattered that they do not allow for us to conclude with any certainty whether the Ghyben-Herzberg relationship holds in the model area or not.

2) Another way of investigating if the Ghyben-Herzberg relationship holds is by making a scatter-plot over the depth to the halocline versus the water level. Ideally, if the Ghyben-Herzberg relationship should hold, this should yield data points distributed along a line with a slope of -40.

Unfortunately, data on the water level and the depth to the halocline have not been available for the same locations. In order to construct this plot in spite of this fact, the measured water level data available to us were paired with the depth to the halocline read from Beddows (2004) or measured by us, if the distance to the coast was the same. This procedure thus assumes that the data are purely governed by the distance from the coast, and therefore neglects any local changes there might be in e.g. hydraulic conductivity, which may affect the data. Despite this assumption which is known not to be valid in reality, the data are plotted here in this way anyway, for illustrative purposes.

Since in some cases there were many data entries for the same distance from coast, but with widely different water table values and/or depths to the halocline, it was chosen to average these values. Thus, for each kilometer from the coast, the average measured water table height was calculated, and the average depth to the halocline was calculated, based on the data. In addition, the standard deviations for each kilometer from the coast were calculated. In cases where there was only one point, a standard deviation of 5 m was assigned to the point, both for the water table data and for the data on the depth to the halocline. These averaged data are plotted in Figure 5.7.



Water table depth [masl]

**Figure 5.7**. Water table depths versus depth to halocline in the model area, based on the collected data presented earlier. Since it was not possible to obtain x- and y-values corresponding to the same locations, the data have been paired corresponding to the same distance from coast. Values have been averaged for each kilometer from the coast, so that all halocline data from 0 to 1 km from the coast have been averaged and plotted against the average of all water table values from 0 to 1 km from the coast, and so on. The standard deviations of the data are also shown. Note that axes to not have the same scale.

By visual inspection, the fit with the ideal line of slope -40 does not seem to be very good. However, in order to quantify the fit, the MSE weighted with the standard deviation of the water table data has been calculated, for the fit to a line with slope -40, and for the fit to a line with slope -15 as suggested by our fitted analytical models, as well as to a line with a slope -24, as suggested by Moore *et al.* (1992) to be valid for their research locality 2-4 km from the Caribbean coast 9 km south of Playa del Carmen. These MSE values are shown in Table 5.4. As seen, according to these data, the Ghyben-Herzberg relationship does not describe the data as well as other possible relationships, especially as the relationship found by the fitting of the analytical models. However, it must be taken into account, that, as mentioned earlier, the water table data are very scattered and with great uncertainties, and also the scatter-plot does not take into account that different conditions locally may influence water table height or depth to the halocline, e.g. a locally higher or lower hydraulic conductivity, since this is disregarded by plotting the data in the way it has been done.

**Table 5.4**. Mean square error (MSE) of the fit of the data plotted in Figure 5.7 to lines with different slopes, reflecting different relationships between the depth to the halocline and the height of the groundwater table.

	MSE, weighted with the standard deviation of the water table data (dim. less)
Fit to line with <b>slope -40</b> and intercept 0 (Ghyben-Herzberg relationship)	507
Fit to line with <b>slope -24</b> and intercept 0 (relationship found to be valid for the study location of Moore <i>et al.</i> (1992) )	254
Fit to line with <b>slope -15</b> and intercept 0 (relationship between water tables and depths to halocline if using the best-fitted analytical models found in this report)	37

Concluding, it can be said that the data cannot confirm that the Ghyben-Herzberg relationship is valid in the model area. The reader is reminded that Beddows (2004) found that the Ghyben-Herzberg relationship does not hold for the conduit locations she investigated in our model area, and Moore *et al.* (1992) found that the Ghyben-Herzberg relationship does not hold for their study location located 2-4 km from the coast just north of our model area. Thus, it is currently not possible for us to say whether more accurate data of the depth to the halocline, e.g. colleted with ProTEM47 measurements, could be translated into water table levels which could be used for calibration of a regional hydrological model by using the Ghyben-Herzberg relationship. However, the issue needs to be investigated further in the whole model area with data on water tables and depth to the halocline corresponding to the same locations and located in various parts of the model area.

## 5.3.5 Point Interpolation of Observed Heads

The 1D plot of head elevations as a function of the distance to the coast is not able to give any information on the two dimensional pattern of the groundwater surface. Therefore a 2D representation of the groundwater surface in the model area has been computed by interpolation of a point map of the observed head elevations, to give a spatial overview of the data. It has been found that the type of interpolation that produces the best fit to the observed heads is a second degree polynomial trend surface interpolation in ILWIS (2005). In the trend surface interpolation operation a polynomial surface is calculated by a least squares fit so that the surface approaches all point values in the map. Also the nearest neighbour (thiessen) and kriging options were tested but with poor results.

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Figure 5.8. Result of 2nd order trend surface interpolation of observed heads.

The computed groundwater surface is seen in Figure 5.8 and shows the expected coastward decrease of head elevations in the model area. The figure also suggests that the elevation of the water table is highest in the southern part of the model area, as is expected for the central part of an island or peninsula. It should however be emphasized that the figure does not show the actual water table surface, but merely gives an overview of the general trend, due to the relatively few data points and their scattered, unevenly distributed nature and the general uncertainty of the data.

## 5.3.6 Averaging of Heads Data for Use in Hydrological Model Calibration

As already mentioned the quality of the observed data is not convincing, as there are examples of several metres of difference in heads between neighbouring observation points, and it will thus be extremely difficult to calibrate a groundwater model to this data. Therefore, the observed heads have been averaged over a 10 km x 10 km grid to smooth the data while still maintaining local contours. This has resulted in 90 observation points. The spatial distribution of these points is seen in Figure 5.9.



**Figure 5.9**. Spatial distribution of head observation points after averaging over a 10 km x 10 km grid (left). The distribution of raw data is shown as reference (right).

A plot of the averaged head elevations as a function of the distance from the coast is seen in Figure 5.10 along with the best fit of the analytical solution to these data. The averaged heads dataset has been analysed for statistical outliers in Matlab, whereby two data points were eliminated. The best fits for the analytical solution are listed in Table 5.5. It is seen that the found values for the hydraulic conductivity are lower than for the fit with the raw data.

The model fit is evaluated with respect to the mean square error (MSE) weighted with the standard deviation of the head values as expressed by Equation 5.1:

$$MSE = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{obs_i - \text{mod}_i}{\sigma_i} \right)^2$$
(Eq. 5.1)

where *n* is the number of observations,  $obs_i$  is the *i*'th observed value, i.e. here the *i*'th averaged head value ,  $mod_i$  is the corresponding modelled value and  $\sigma_i$  is the standard deviation of the *i*'th observed value. MSE weighted with the standard deviation is thus unitless.

The standard deviations indicated with error bars on Figure 5.10 and used for calculation of the model fit have been read from the map where possible, i.e. where more than one observation has been present in one grid cell. Where only one observation has been present in a grid cell the standard deviation has arbitrarily been set to 5 m. From Figure 5.9 it is seen that some of the grid cells and thereby also the corresponding observation points are located in the "sea". These points have been set to be located on the coastline, i.e. distance from coast has been set to 0 m.

The head observations are still very scattered as the range is  $\sim$ 30 m over a distance of 120 km. However, this dataset represents the current level of knowledge of water levels and will be used in the calibration of the regional-scale hydrological model.



**Figure 5.10**. Head observations as a function of distance from the coast for averaged over a 10 km x 10 km grid. Standard deviations are illustrated with error bars. Outliers are indicated with red arrows.

**Table 5.5**. Results of fit of the analytical model to 10 km x 10 km averaged head data. Recharge fixed, hydraulic conductivity variable

Recharge (r) [%]	Recharge (r) [m/day]	Hydraulic conductivity ( <i>K</i> ) [m/day]	Hydraulic conductivity ( <i>K</i> ) [m/s]	Mean square error (dim. less) (weighted with st.dev)	Root mean square error (dim. less) (weighted with st.dev)
15	0.0005	3000	0.03	2.76	1.66
30	0.001	6000	0.07	2.76	1.66
45	0.0015	9000	0.10	2.76	1.66
60	0.002	12000	0.14	2.76	1.66

## 5.4 Summary and Conclusions

The water table data are extremely important for the groundwater modelling, as at present this is the only parameter that it is possible to calibrate the groundwater model with. However, as the analyses performed in this chapter have shown, it is evident that the data are not of a high quality and that strong approximations have had to be made. Nonetheless these are the data currently available and will be used to make a first regional hydrological model of the area.

The analyses presented in this chapter have shown that head elevations can be expected to range between -7 and 16 m above mean sea level, however the unreasonably low values are believed to be due to false estimation of surface elevation of observations points especially close to the coast. Hydraulic conductivities computed from the analytical solution range from 0.07 m/s at a low recharge rate (15% of mean annual precipitation) to 0.26 m/s at high recharge rate (60% of mean annual precipitation). Assuming a low permeability layer in the near-coastal zone (0-1 km) did not show any difference in this result. For an averaging of the head elevation measurements over a 10 km x 10 km grid the hydraulic conductivities obtained from fitting the analytical 1D model ranged from 0.03 m/s to 0.14 m/s (MSE 2.76 weighted with the standard deviations). Form this analysis it is evident that the aquifer is highly permeable since the *K*-values found are in the high end of the scale of hydraulic conductivities for the Yucatan Peninsula mentioned in the literature (presented in Chapter 2 and Appendix B).

From the literature and analysis of available data is seen that seasonal variations in freshwater heads are small (< 0.5 m) and that the aquifer seems to react more to short term variations in conditions such as extreme rain events, barometric pressure, tides and ocean density, while there is not much change on a long-term scale. This suggests that the baseflow originates from the interior part of the peninsula and that variations observed in cenotes and boreholes in the coastal zone are mainly due to the short term variations and that changes in recharge does not significantly affect the water table elevation. This also means that the aquifer can be considered quite stable and that day-to-day fluctuations are insignificant for a regional hydrological model, which therefore as a first approximation can be made steady-state.

Based on the data for depth to the halocline presented in Chapter 4 and the head elevations presented in this chapter it has been shown that the Ghyben-Herzberg relationship stating a 1:40 proportionality factor between the extent of the freshwater lens above and below mean sea level does not seem to be valid, at least with the data available for the present study. Instead it seems a 1:15 proportionality factor fits better to these data. It cannot, however, be ruled out that the Ghyben-Herzberg relationship may hold in parts of the model area, because the majority of the data on the depth to the halocline stem from ares of high permeability which can cause a thinning of the freshwater lens. Where such high permeability zones are not present it is therefore possible that the Ghyben-Herzberg relationship may hold, and this should be investigated further in the future.

# AQUIFER STRUCTURE

# AQUIFER STRUCTURE

The karstic nature of the aquifer means that water flows not only in a matrix but also in dissolution conduits. In addition, physiographic features such as faults and fractures may influence the flow. The following two chapters analyze structural features of the aquifer further. First, areas with potential high permeability are delineated. This is followed by an investigation with geophysical equipment over some of these structures to confirm their existence in the aquifer.

# 6 Identification of Potential High Permeability Areas in the Aquifer

The aquifer structure is a determining factor for the groundwater flow patterns of the model area. Since the aquifer of study is a karstified medium, the groundwater flow takes place in three different compartments: in the rock matrix, in fracture networks and in conduit networks, as explained in Chapter 2. These three compartments have widely different permeabilities and flow patterns. While matrix flow is flow between interconnected pore spaces, fracture flow is flow in openings ranging from 0.01 or 0.1 mm to 10 mm in width, and conduit flow takes place in openings ranging from 10 mm to tens or even hundreds of meters (White, 2003).

For a regional-scale hydrological model of the area especially information on the pattern and spatial extent of large-scale zones of high permeability is important to obtain. In particular, this may be the location of fault zones, or areas with conduit development, since flow velocities in the conduits are greater than in the matrix and the fracture networks (Atkinson, 1977; Worthington, 2003). Generally, the location of these features in the model area that potentially govern groundwater flow is not known, apart from the known cave developments described in Chapter 2. Therefore, in this chapter, inspection of satellite imagery is combined with data on cenote density, topographical data and data from published maps to identify zones of potentially higher permeability throughout the model area.

## 6.1 Delineation of Potential High Permeability Areas

Several types of features may be associated with higher permeability and secondary porosity flow:

- Faults and fractures.
- Areas with known conduit development.
- Areas with high cenote density.
- Structures distinguished from satellite imagery.

In the following the presence and extent of these feature types in the model area will be presented.

## 6.1.1 Faults and Fractures

Faults and fractures are secondary porosity features, which have a high permeability of their own, and in addition, conduits are often seen to develop along fractures. Therefore it makes good sense to assume higher permeability at the locations of faults and fractures, or at least to look for other features that indicate higher permeability in areas with fracturing.

Figure 6.1 shows the distribution of faults (orange lines) and fractures (yellow lines) in the model area according to the map of INEGI (no year).

The map of INEGI (no year) displays some of the northeast oriented Rio Hondo faults in the southern part of the model area, and the Sierrita de Ticul fault is seen. The locations of the Rio Hondo faults, the Sierrita de Ticul fault, the Holbox fracture zone and the fault suggested by Perry *et al.* (2002) were discussed in detail in Chapter 2, and will therefore not be repeated here.



**Figure 6.1**. Distribution of faults (orange) and fractures (yellow) in the model area, digitized from INEGI (no year), and displayed on the background image of the SRTM topography map (USGS, 2004), enhanced with the "Hillshade" function in ArcGIS, with light source from northwest and azimuth of the light source of  $45^{\circ}$ . Grey dotted boxes indicate the two apparent groupings – the inland fractured area and the coastal fractured area. The coastal fractured area may be divided into two subgroups, a southern with a higher fracture density; and a northern with a lower fracture density.

The fractures displayed on the map of INEGI (no year) are primarily oriented northeast, but also a significant part of them are directed southeast, as seen from the rose diagram in Figure 6.2, which illustrates the orientation of the fractures, and their frequency (number of lines in the diagram), as well as their individual length. From the map, it seems that the fractures can be divided into two main areas. One is inland, in the older geologic material, where there are a number of fractures, but where the fracture density is relatively low. When consulting the SRTM topographical map (USGS, 2004), it is seen that this inland area is located at relatively higher altitudes, generally > 50 m above mean sea level, and in an area with an undulating relief. The undulations are caused by compressive deformation in the Eocene,

and so are the inland fractures, which are described as "slight deformations with small structural closings" (Butterlin & Bonet, 1963, cited by INEGI, no year).



**Figure 6.2**. Rose diagram showing the direction of fractures in the entire model area. 0° indicates direction due east, while 90° indicates north.

The second area of fractures is located in a belt from the coast up to about 70 km inland (some places though only up to 30 km from the coast). The density of fractures here is much higher. The fracture density is particularly high west of the border of Sian Ka'an, especially from the northern part of the reserve towards the middle of the reserve. This area is notable, because the fractures have a dense, criss-crossing pattern. The topography here is low (< 30 m above mean sea level (USGS, 2004)). Faults and fractures in this coastal area are believed to have been formed in the Miocene/Pliocene (Butterlin & Bonet, 1963, cited by INEGI, no year). Possibly the fractures in this coastal area can be divided into a northern and a southern section, since fracture density seems to be lower in the northern area, which is located just north of the model area along the east coast.

Judging from rose diagrams made of the fractures of each area there does not seem to be a notable difference in the prevalent fracture directions from area to area (see Figure 6.3 to Figure 6.6).



Figure 6.3. Direction of fractures in inland area.



Figure 6.4. Direction of fractures in coastal area.



Figure 6.5. Direction of fractures in coastal area, north.

Figure 6.6. Direction of fractures in coastal area, south.

Between the inland and the coastal main fracture areas in our model area there is a 'void', i.e. an area, where according to INEGI (no year) there are no fractures. This can of course be due to lack of knowledge of the area, but since the other areas have a rather even distribution of fractures, another explanation may be possible. The area without fractures is located in an area which, according to Shaw (pers. comm., 2006), seems to have been subject to extensive folding, and which has a different altitude level ( $\sim$  30-50 m above mean sea level) than the two other areas. That this area is much more folded is likely judging also from the SRTM topographical map and field observations from driving in the area<sup>8</sup>.

Due to the spread of fractures in some parts of the model area, only areas with a high density of fractures is here considered as possible areas of high permeability, and has been grouped as such. Extensive fracturing is seen in the area east and north of Felipe Carrillo Puerto, as displayed in Figure 6.7. As will be seen in the sections below, the area east of Felipe Carrillo Puerto coincides with an area of high cenote density, whereas the fractures further north to some extent coincide with other identified structural features. Although caves are known to develop along fractures, none of the fractures identified by INEGI (no year) coincide with the area of extensive known cave development, as will be seen below. This illustrates that the fracture map may only show a fraction of the actual fractures in the area, but it is the only fracture data available at the moment.

<sup>&</sup>lt;sup>8</sup> Wavy hilly terrain was encountered in this area. Some apparent small folds were quite regularly spaced and in the same direction, while in other places, direction of the folds varied widely.



**Figure 6.7**. Fractures in the northern part of the model area (yellow lines). Background map is SRTM topographical map (USGS, 2004), enhanced with the "Hillshade" function in ArcGIS, with light source from northwest and azimuth of the light source of 45°.

## 6.1.2 Areas with Cave Development

As mentioned in Chapter 2, two major cave systems are located in the model area, namely Ox Bel Ha south of Tulum and Sac Actun north of Tulum. The caves extend ~12 km inland from the coast (Coke, pers. comm., 2006; Meacham, pers. comm., 2006; Schmittner, pers. comm., 2006; Beddows, 2004).

Explored cave systems at the Caribbean coast trend northwest to southeast, nearly perpendicular to the coastline (Beddows, 2004). However, the Caapechen cave system inside the Sian Ka'an Biosphere Reserve also displays southwest to northeast directions. There is a high degree of interconnection between parallel conduits in the explored cave systems from Tulum to Xel Ha, as also illustrated by a relatively high conduit density reported for this area of  $\sim 2$  km conduit pr. km<sup>2</sup> (Beddows, 2004).

As discussed in Chapter 2, the cavernous area described here may correspond to the area with Pleistocene geology, which in the Tulum area according to Shaw (pers. comm., 2006) ends around cenote Carwash, located  $\sim$ 12 km inland from the coast. From Figure 6.8 it is seen that the Pleistocene geology according to Ward (no year) generally extends further than indicated by the map of INEGI (no year).



**Figure 6.8**. Left: Geological map of Pleistocene units in northern Quintana Roo according to Ward (no year). Right: and location of the Pleistocene geology (green colour) according to INEGI (no year), displayed on the background SRTM topographical map (USGS, 2004), enhanced with the "Hillshade" function in ArcGIS, with light source from northwest and azimuth of the light source of 45°. Yellow lines indicate fractures. Blue areas are lakes from a shape file kindly provided to us by Amigos de Sian Ka'an. The two figures show the same area but since the figure from Ward (no year) is hand drawn there are some discrepancies and distortions, and the drawing by Ward is slightly tilted compared to the right image, as can be seen on the north arrow. However, the scale and area depicted are the same.

The explored caves north and south of Tulum cannot be seen on satellite imagery. Therefore, line maps have been used to identify the cave areas. Since areas with known cave development seem to correspond well with the extent of the Pleistocene geology, for the delineation of high permeability areas it is therefore assumed that the entire Pleistocene geological unit has high permeability.

The map from Ward (no year) in Figure 6.8 (left) has been used to delineate the Pleistocene geological unit, since the map from INEGI (no year) fails to recognize the existence of this unit as far inland as reported by Ward (no year) and Shaw (pers. comm., 2006).

Northward, the Pleistocene unit extends beynd the border of the model area. The southern border of the Pleistocene is however not well known. The Ox Bel Ha cave system begins to stretch south at its most inland point, which corresponds well with the pattern of the landscape as seen on satellite imagery. This could indicate that the Pleistocene curves around the Sian Ka'an Biosphere Reserve. Inside the Sian Ka'an Biosphere Reserve the geology seems to be different from that north of the reserve, according to the reports from the diving explorers of the Caapechen and Ox Bel Ha systems (Le Maillot, pers. comm., 2006; Devos, pers. comm., 2006; see also descriptions in Chapter 2).

Therefore, it is assumed that the Pleistocene geology, and hence the assumed area of extensive cave development, ends between Ox Bel Ha and Caapechen. This is also done based on the topographic map in Figure 6.9 that shows a visible change in elevation at the southern border of the Ox Bel Ha cave

system, here illustrated by the southern border of an area of high cenote density. Although this topographic map and the geological map of Ward (no year) (Figure 6.8, left) could indicate that the Pleistocene curves around the Sian Ka'an Biosphere Reserve in a narrow belt that thickens further south, it has been decided not to include this area as an area of assumed extensive cave development due to the lack of information to support this.



Figure 6.9. SRTM topographic map (USGS, 2004) and location of cenotes identified by INEGI (no year), Coke (pers. comm., 2006), Meacham (pers. comm, 2006), Schmittner (pers. comm., 2006) and our selves. Legend unit is m.a.m.s.l.

## 6.1.3 Areas with High Cenote Density

Because the cenotes may be formed by either a slow or a sudden collapse of the roof of an underground conduit (Escolero *et al.*, 2000). They may therefore be indicative of areas with high permeability. However, as mentioned in Chapter 2, cenotes are not always part of cave systems but may also be isolated dissolution holes.

As presented in Chapter 5 INEGI (no year) has noted the location of 28 cenotes, which have been used for measuring water levels. They are therefore not representative of the actual cenote distribution in the area. The cenotes from INEGI (no year) are only located in the northern part of the model area, but they are relatively spread out. The map of INEGI (no year) thus shows that cenotes are not only located close to the coast, but also inland.

The cenotes registered by the cave explorers Coke, Meacham and Schmittner (pers. comm., 2006) are far more numerous (> 800). Their registered cenotes are located from Muyil in the south and ~ 100 km north of there, and up to ~ 45 km from the coast, which yields an overall cenote density of ~ 0.17 per km<sup>2</sup>. In the area with the highest density of registered cenotes, which is a ~13 km wide belt on the 45 km stretch between Muyil in the south and Akumal in the north the density is ~ 1.2 per km<sup>2</sup>. The pattern of the registered cenotes reflects the locations where most of the cave explorers typically come, as well as general accessibility, as also noted by Beddows (2004). However, the high density of cenotes between Muyil and Akumal is also a reflection of the higher abundance of known underground conduit systems here.

The cenotes mapped by us during our field trip show that there are also cenotes inland and south of the areas mentioned above. Even in the area where seemingly there are no fractures, cenotes have been found. However, when talking to people in these areas and asking about cenotes, it is our impression that they are not distributed with a high density in these areas, and it was often necessary to drive tens of kilometres to get to the next known cenote.

Thus, it seems that generally cenotes are distributed all over the model area, with higher or lower density. Also the names of villages confirm that cenotes may be encountered inland, as villages are often developed around large cenotes and also their names may include the word "dzonot" (- Maya for cenote). No representative map over the actual cenote density and location in the model area currently exists, since problems such as accessibility, the size of the area and the motivation to make such an inventory, has hindered that anybody has made such. Possibly the cenote density is largest in the coastal area east of the Holbox fracture zone, in the Pleistocene area of Tulum to Xel Ha, where also many conduit systems have been found. There is no particular correlation between mapped fractures (INEGI, no year) and the presence of cenotes, as shown in Figure 6.10.

On satellite imagery, many cenotes can also be identified by visual inspection. Thus, the information presented in Figure 6.10 has been supplemented with these data for delineation of areas with high cenote density. For example, such an area is located east of Felipe Carrillo Puerto, as shown in Figure 6.11.



Figure 6.10. Distribution of cenotes relative to faults and fractures (INEGI, no year). Locations of cenotes aggregated from different sources: INEGI (no year), Coke, Meacham & Schmittner (pers. comm., 2006) and own field data.



**Figure 6.11**. Example of an area with a high density of cenotes northeast of Felipe Carrillo. The cenotes are seen as black circular features on the satellite images from Google Earth (2006). Some of them are highlighted on the image with white arrows. Note, however, that some of the dark features near the white cloud features are cloud shadows and not cenotes.

## 6.1.4 Structures Distinguished from Satellite Imagery

As is evident from the above, known areas of high permeability, e.g. cave development, are currently mainly found in the coastal areas where there is also a greater degree of accessibility. To investigate the presence of zones elsewhere in the model area with secondary porosity flow capable of directing large amounts of infiltrated rainwater, a Landsat ETM+ multi-spectral satellite image has been analyzed. Computational image treatment was first attempted in order to obtain a more objective analysis of the images. However, these efforts were found not to find obvious structures in the landscape, which could be seen by visual inspection, and were found to be subject to significant amounts of noise. These results of the digital image processing will therefore not be presented here, but can be found in Appendix I. In the following, only the results of the visual inspection of the images have been overlain on one of the digitally analysed images, and it is seen that although a few of the structures near Rio Hondo were found by the digital

image analysis, the visual inspection has found far more potential high permeability areas, and finds structures in a greater part of the model area than the digital image analysis does.

## 6.1.4.1 Visual Inspection of Satellite Imagery

Visual inspection of satellite images have therefore been used for identifying further potential areas of high permeability. The identified structures can be classified into two types:

- Open water bodies and subsurface continuations following an obvious line in the landscape.
- Structural features not immediately associated with water.

The structures have partly been identified on Landsat ETM+ multi-spectral images covering the area. However, the freeware programme Google Earth provides a seamless satellite image of the entire Earth, and over the Yucatan Peninsula the resolution of these images is often better than that of the Landsat ETM+ images. This high resolution image from Google Earth (2006) has therefore also been used to visually identify areas where it is assessed that there is a potential for high hydraulic permeability in the subsurface.

## Open Water Bodies and Subsurface Continuations Following an Obvious Line in the Landscape

Structures of this type are likely to represent runoff flow paths for surface waters, and they can to some extent be correlated with the flooded areas indicated on the map from ITMB (2005), but not always. The visual interpretation of these areas have revealed what seems to be a large surface runoff/drainage area in the area west of the line of lakes southwest of Felipe Carrillo Puerto (Lakes Kaná, Cacaoche, Dzidzantún and Tzepop and Lakes X-Kojoli, Sac-Ayin, Xpaitoro and Petén Tulix further south) (Figure 6.12).



Figure 6.12. Overview of the lakes located southwest of Felipe Carrillo Puerto. Image from Google Earth (2006).

At Lake Kaná there is a closed depression area. The depression is very steep with a height difference between the surrounding ground surface and the lake of  $\sim 20$  m according to the topographical map from SRTM (USGS, 2004). According to Shaw (pers. comm., 2006) Lake Kaná receives water from surrounding areas but there is no obvious drainage from this lake as is also seen in Figure 6.13, where there is no visible surface sign of an underground high permeability area heading towards the coast from the lake. Therefore, the drainage from the area may take place via subsurface flow from Lake Kaná towards the coast (Shaw, pers. comm., 2006).



**Figure 6.13**. Lakes Kaná, Cacaoche, Dzidzantún and Tzepop. There is no visible flow from these lakes towards the coast. Image from Google Earth (2006).

Shaw (pers. comm., 2006) also believes that the lakes further south must drain underground. This is supported by the images in Figure 6.14 that show that the lakes seem to be natural reservoirs along an underground high permeability area that meanders towards the west ending with the Lake Ocom just south of Felipe Carrillo Puerto. Along the entire structure there are extensive agricultural areas indicating availability of water.

Also several large structures of this type are located in the southern part of the model area, west of Chetumal Bay.



Figure 6.14. Lakes X-Kojoli, Sac-Ayin, Xpaitoro and Petén Tulix and the potential shallow subsurface flow paths, obvious as lines in the landscape, surrounded by agricultural fields. Images from Google Earth (2006).

#### Structural Features Not Immediately Associated with Water

These features are lines in the landscape that cannot readily be associated with water flow. Examples of such structural features are depicted in Figure 6.15, where the first image shows two half moon shaped features that are not as green as the surroundings. Similarly, the second image is of a long, almost linear feature, which shows the same characteristics. The structures are mainly visible in and around the Sian Ka'an Biosphere Reserve as the many agricultural activities further inland makes them difficult to see, should there be any. Another reason that these structures are not visible further inland could be the difference in depth to the groundwater. Where the groundwater is close to the surface, the structural features could have an impact on vegetation patterns, if associated with underground water flow.



**Figure 6.15**. Examples of structural features in the landscape. Left: half moon shaped features on the left side of the road. Right: long feature on the right side of the road. Images from Google Earth (2006). Location of the two pictures is indicated on Figure 6.16 with white dotted boxes.

Figure 6.16 indicates the presence of some of these structural features (indicated with green dots on the figure). They are seen to coincide with areas where there are fractures (yellow lines) according to the maps of INEGI (no year). Either we have therefore been able to visually see fractures on the satellite image, or our structures are correlated with fracture zones. In any case, the good correspondence with these structures and the INEGI fault lines shows that it is reasonable to assume that there is a higher permeability in the areas where we have identified structures. That these structures can be zones of higher permeability will be investigated further in Chapter 7.



**Figure 6.16**. Correspondence between structures identified from visual inspection of a Landsat ETM+ satellite image before field trip and areas of faults and fractures digitized from INEGI (no year). White dotted boxes indicate the location of the images shown in Figure 6.15.

## 6.2 Overview of the Identified High Permeability Areas

Figure 6.17 shows an overview of the high permeability zones identified by visual interpretation of satellite imagery in combination with knowledge of geology, as well as the location of known caves and cenotes. The different types of high permeability zones have been combined into one figure in Figure 6.18, and as seen in the area around Tulum where there are conduits and cenotes, the high permeability area has been extended to include the entire area covered by the Pleistocene geology as interpreted from

the definition by Ward (no year). Also the area with high cenote density east of Felipe Carrillo Puerto has been extended to include the fractures in this area.



**Figure 6.17**. Identified areas of potentially high permeability. From top left: Area with known conduit development (blue); High cenote density area (orange): Open water bodies and shallow underground continuations (red); Structural features in the landscape not immediately associated with water flow (green). Faults (orange lines) and fractures (yellow lines) as digitzed from INEGI (no year). Background image is the SRTM topography map (USGS, 2004), enhanced with the "Hillshade" function in ArcGIS, with light source from northwest and light azimuth 45°. Location of submaps indicated on top overview figure, each location marked with their respective colour.



**Figure 6.18**. Overview of the identified high permeability zones (blue). Faults (orange lines) and fractures (yellow lines) as digitzed from INEGI (no year). Background image is the SRTM topography map (USGS, 2004), enhanced with the "Hillshade" function in ArcGIS, with light source from northwest and light azimuth 45°.

It is evident from Figure 6.18 that the structures in the southern part of the model area generally stretch from the inland part of the peninsula towards the coast in a north-eastern direction and seem to be associated with flow of water that for the main part is occurring underground at shallow depth, but occasionally surfaces. The structures in the northern part of the model area (north of Felipe Carrillo Puerto) are mainly structural features not apparently associated with water, or are associated with geological features such as faults and fractures or the Pleistocene geology.

In general the depth of the various types of high permeability zones are not known, except from the caves around Tulum, which have their deepest points approximately 25-30 m below mean sea level  $\sim$ 12 km inland.

The identified high permeability zones on Figure 6.18 will be used as a scenario in the regional hydrological model. The possible prolonging of the Rio Hondo faults, the fault suggested by Perry *et al.* (2002) and the possible prolonging of the Holbox fractures zone, as discussed in Chapter 2, are not included in Figure 6.18 since they will be treated as separate scenarios in the modelling.
# 7 Analysis of Structures with Geophysical Methods

In order to investigate the structures present in the model area, investigations have been carried out using the frequency domain electromagnetic system EM34-3 XL from Geonics Ltd. Canada. To evaluate the applicability of the method for detecting structures such as underground conduits, the instrument has been applied in the model area over a section of known cave. A clear anomaly has been seen where the conduit is located, at two independent measurement times. This result is shown in Figure 7.1. The anomaly has values of > 25 mS/m, whereas the background level is between 20 and 23 mS/m. This is a generally high background value compared to what will be seen later in this report. The reason is that the transect is located in an area with a generally high level of cave development, so that smaller caves may be crisscrossing the areas where background values are measured. The location of this measured transect and the cave line map cannot be shown here, because the authors do not have the rights to publish these particular cave line maps.

The measurement over the known cave confirms that it is possible to detect underground conduits with the EM34 equipment, and was the reason why EM34 measurements were carried out at the locations which will be described in the following.



**Figure 7.1**. EM34 measurement made over known cave near cenote Cristal, using 20 m coil spacing. The anomaly with values higher than 25 mS/m indicates the location of the cave. March data courtesy of Supper *et al.* (submitted).

The geophysical measurements with EM34 have been applied as a step in the process to identify regional zones of higher hydraulic permeability in the model area. One of the ground-based electromagnetic surveys has therefore been carried out over one of the structures identified in the previous chapter, to investigate whether this type of structures are in fact indicative of a zone of higher hydraulic permeability. This is the so-called Vigia Chico Road measurement presented in the following.

In addition, an electromagnetic survey has been conducted over an area located near the Holbox fracture zone, to investigate the correlation between this zone and conduit development/zones of high permeability. The location was selected based on inspection of aerial photos as well as accessibility considerations.

Finally, a survey has been conducted within the Sian Ka'an Biosphere Reserve, to investigate an area close to where cave divers have explored a cave system, in order to assess the applicability of the method in a brackish water environment and attempt to find out which directions the explored cave would take. This is the Caapechen measurement described lastly in this chapter.

The term anomaly used in the following is defined as measured values deviating from the measured background values. The deviation is based on visual inspection of the graphs, and is thus to some extent subjective. However, forward modelling is carried out to investigate the seemingly anomalies further, to substantiate if they are in fact real anomalies arising from underground conduits or they are just variation having other causes.

All coordinates and associated EM34 readings from the sites can be found in the DVD-appendix.



**Figure 7.2**. Left: Model area (red line), the Sian Ka'an Biosphere Reserve (green line), the area enlarged in the image to the right (black square). Right: EM34 survey locations, on a background image from Landsat ETM+.

### 7.1 The Vigia Chico Road Measurement

#### 7.1.1 Location and Results of the Measurement

Of the identified satellite structures, EM34 measurements has been made on a 5770 m long stretch which crosses the structure shown in Figure 6.15 (right) and which is located along the road to Vigia Chico (in the following called the Vigia Chico Road measurement).

The results from this EM34 measurement are seen in Figure 7.2. As seen in the figure, measurements have been made with 20 m coil spacing, and on a part of the stretch in the area where an anomaly seemed to be detected, measurements have also been made using a coil spacing of 40 m. This latter stretch was 1022 m long. For the 20 m coil spacing in the horizontal dipole mode that we used, 75% of the signal comes from a depth of zero to 15 m below ground, and the other 25% comes from below the 15 m, whereas with the 40 m coil spacing, 75% of the signal comes from the ground surface down to 30 meters depth below ground, while the remainder is from below 30 m depth. This is a consequence of Equation 3.3 presented in Chapter 3. The penetration depth is thus larger for the 40 m coil spacing. Measurements have been spaced 5 m apart in the middle section where the apparent anomaly is detected, and in the other sections, spacing between measurements is 20 m or 40 m, approximately.



Vigia Chico Road

Figure 7.2. Apparent conductivity measured with the EM34 along the Vigia Chico Road transect.

By visual inspection of the graph of the ground apparent electrical conductivities in Figure 7.2, the background level of conductivity in this environment seems to be values from 9 to about 17 mS/m. That is, all measured values in this stretch below 17 mS/m are regarded to be background values reflecting limestone strata with no significant conduit development. Whether this is reasonable will be investigated with the forward modelling below. The decrease in signal down to 6 mS/m around 2600 m from the northern end is ascribed to be interference from a nearby parked car, and should be disregarded.

Based on the visual inspection of the results a signal larger than 20 mS/m is defined to indicate an anomaly on this Vigia Chico Road stretch, i.e. a signal which is significantly different from the background value.

It is seen that one larger anomaly, 890 m wide, has been detected, with values of the signal up to 36 mS/m using both the 20 m and the 40 m coil spacing. Furthermore, a more narrow anomaly, 78 m wide, has been detected having signal values up to 24 mS/m.

The locations of these two anomalies are marked in red on Figure 7.3 which shows the location of the measured transect in red and green. In this figure, the identified structure is marked with dots, going in a south-southwest north-northeasterly direc-tion. It is seen that the wide anomaly seems to correspond very well with the identified structure. No obvious structure is found near the second anomaly, which could be due to it being very narrow.



**Figure 7.3**. The Vigia Chico Road transect (red and green). Red colour indicates the location of the anomalies. Brown dots are placed along the structures identified on the satellite imagery. Background image is Landsat ETM+ imagery.

#### 7.1.2 Modelling of the Results

The method of EM34 does not allow for converting the measured signal into a 1-D geologic model properly, because the 5 model parameters – resistivities of each layer and depth to the layers - are in principle all free, and the measured signal is an aggregate of the whole underground configuration. Thus, it may be used to detect that there is an anomaly present, but cannot in detail give information about the resistivities and depth of underground layers.

Nevertheless, forward modelling with Equation 3.2 and 3.3 from Chapter 3 has been initiated to analyze which underground configuration could lead to the observed signals, and whether the anomalies could be caused by the presence of underground conduits.

On beforehand, expected values for geologic materials of the location were obtained using literature values and measured values. This was done to restrict as many of the model parameters as possible to reasonable values.

Values have been fixed for the following parameters:

- Resistivity of unsaturated zone: <u>1000 Ohm-m</u> (according to values measured by Supper *et al.* (submitted results, from geoelectrical profile conducted at Cenote Box Chen and Cenote Bomba), and according to Rebolledo-Vieyra (pers. comm., 2006))
- Resistivity of freshwater lens in limestone: <u>300 Ohm-m</u> (according to values measured by Supper *et al.* (submitted results, from geoelectrical profile at Cenote Escondido and Cenote Box Chen, and same range as reported by Rebolledo-Vieyra (pers. comm., 2006))

Resistivities of freshwater in underground conduits is a parameter to be investigated in the modelling, but Supper *et al.*, (submitted) found values of conduit resistivities of about 10-75 Ohm-m at Cenote Escondido, and of about 30-100 Ohm-m at Cenote Bomba.

- Depth of unsaturated zone:

Value was selected according to distance from coast, chosen within the general approximate range reported by Beddows (2004) of: 20-50 m thickness when site is more than 10 km from the coast, and up to ca. 10 m thick in an area of up to 10 km from coast. This information generally is for the area north of Sian Ka'an from ca. Tulum to Xel Ha, but it is assumed that these general values are also valid in our area of interest.

- Depth to halocline:

The analytical model presented in Chapter 4 and fitted to the halocline data was used to obtain a value for the expected depth to the halocline below sea level.

- Elevation estimates were obtained from the topographical model of the Shuttle Radar Topography Mission (SRTM) (USGS, 2004) and is needed because the forward model uses depth of layer from ground surface, whereas the depth to the halocline is relative to the mean sea level.

Distances from coast were measured on the satellite images using GIS software.

Table 7.1 thus displays the values used for the Vigia Chico Road site.

<b>Table 7.1.</b> Talameter values used for the geologic model of the vigia Chieo Road site.					
Distance from coast:	14	to	19	km	
Ground elevation:	12	to	15	m above mean sea level	
Expected depth to halocline:	37	to	42	m below mean sea level	
Expected depth to halocline:	49	to	57	meters below ground surface (sum of the two above lines)	
Expected thickness of unsaturated zone	15	to	20	m	

 Table 7.1. Parameter values used for the geologic model of the Vigia Chico Road site.

Different combinations of the parameters in the geologic model are first tried out in order to obtain a proper value for the measured background signal of 9 to 17 mS/m.

A first good fit which has reasonable values for all parameters is that shown in Figure 7.4. The apparent conductivity calculated with Equation 3.2 for this configuration is shown below the figure. It is seen that this value is within the measured background conductivity range of 9 to 17 mS/m.

		ρ <sub>1</sub> =	1000 Ohm-m	l	- 20 m
	Π	ρ <sub>2</sub> =	300 Ohm-n	า	
35 m	$\exists$				
	U				- 55 m
		ρ <sub>3</sub> =	7 Ohm-m		

#### Apparent conductivity: $\sigma_a = 14.1 \text{ mS/m} \rightarrow Acceptable background configuration}$

**Figure 7.4**. Acceptable model of the background geology at the Vigia Chico Road transect. The apparent conductivity calculated with Equation 3.2 for this configuration is shown below the figure.

A sensitivity analysis is then employed to evaluate the relative importance of an accurate fit of each parameter. The results are shown in Table 7.2. Resistivities have been varied by 30% while depths of layers have been varied with 10 m, since for the depth, the uncertainty is estimated to be in that range rather than as a percentage. The result of varying the depth to the halocline by 5 m is also shown, since, as it is seen in Table 7.2, the geological model is rather sensitive to this parameter, and 5-10 m is estimated to be this parameter's uncertainty.

As seen from Table 7.2, the model is sensitive to variations in:

- the resistivity of the saltwater layer (Layer 3)
- the depth to the halocline.

Variation by 30% and 10 m, respectively, yields changes of up to 39% in the simulated signal. All other parameters only give a negligible change in the signal (max. 3 % change) when varied by 30% or 10 m.

Parameter varied		Simulated apparent conductivity (σ <sub>a</sub> ) [mS/m]	Abs. change [mS/m]	% change
$\rho_1$	$\rho_1$ increased by 30%, value: 1300 Ohm-m	14.0	-0.1	-1%
	$\rho_1$ decreased by 30%, value: 700 Ohm-m	14.5	+0.4	+3 %
ρ <sub>2</sub>	$\rho_2$ increased by 30%, value: 390 Ohm-m	14.0	-0.1	-1%
	$\rho_2$ decreased by 30%, value: 210 Ohm-m	14.4	+0.3	+2 %
ρ <sub>3</sub>	$\rho_3$ increased by 30%, value: 9 Ohm-m	11.2	-2.9	- 21 %
	$P_3$ decreased by 30%, value: 5 Ohm-m	19.6	+5.5	+39 %
Depth of unsaturated	10 m increase in depth, value: 30 m	14.0	-0.1	+1%
zone	10 m decrease in depth, value: 10 m	14.5	+0.4	+3 %
Depth to halocline	10 m increase in depth, value: 30 m	12.2	-1.9	-14 %
	10 m decrease in depth, value: 10 m	16.9	+2.8	+20 %
	5 m increase in depth, value: 25 m	13.1	-1.0	-7 %
	5 m decrease in depth, value: 15 m	15.4	1.3	+9%

**Table 7.2**. Sensitivity of simulated signal to change in each model parameter. All changes are relative to the baseline value of 14.1 mS/m given in Figure 7.4. Locality: Vigia Chico Road.

Now, the effect of changing the resistivity of the freshwater layer (Layer 2) is investigated. The resistivity is lowered corresponding to the expected effect of the presence of a conduit, i.e. using resistivities of 10 to 50 Ohm-m.

By using the above good fit for the background values, shown in Figure 7.4, with a saltwater resistivity of 7 Ohm-m and a depth to the halocline of 55 m, it is *not* possible to possible to obtain values of up to 36 mS/m, as the actual anomaly had shown. This is seen from Table 7.3.

Table 7.3	. Effect	of	inserting	а	conduit	in	the	baseline	configuration	from	Figure	7.4.	SW=	saltwater.	FW=
freshwater															

	Simulated signal, $\sigma_a$ ,
	using SW resistivity = 7 Ohm-m
	and depth to halocline: 55 m
FW resistivity = 50 Ohm-m	16.6 mS/m
FW resistivity = 20 Ohm-m	21.0 mS/m
FW resistivity = 15 Ohm-m	23.4 mS/m
FW resistivity = 10 Ohm-m	28.2 mS/m

Therefore, some other parameter of the baseline configuration has to be adjusted, to see if it is possible to obtain the anomaly values using reasonable resistivities for a freshwater conduit. From the sensitivity analysis we have learned that this parameter should either be the depth to the halocline or the resistivity of the saltwater.

Although the depth to the halocline is taken from a simple analytical model which has been fitted to data measured in the field by us and others, this parameter may be uncertain by  $\sim$ 5 meters (estimated).

For that reason, a new baseline model has been made where the depth to the halocline is decreased to 50 m below surface. Table 7.4 shows the corresponding simulated background signal as well as the signals resulting from lowering the freshwater resistivity to the conduit range. The simulated background signal (15.4 mS/m) is within the measured range of background values. However, it is seen that with this configuration, it is still *not* possible to achieve the high signals seen at the anomalies, using reasonable resistivities for the freshwater conduit. With a freshwater resistivity of 10 Ohm-m, the simulated signal becomes 28.6 mS/m (Table 7.4), which is 21% lower than the maximum measured anomaly conductivity. For this configuration, a value of 36 mS/m can only be obtained if the resistivity of the freshwater layer is the same as that of the saltwater layer (7 Ohm-m), or if the depth to the halocline would be the same as the depth to the water table. Neither of these cases is realistic since it would mean that no freshwater would be present at this location. Therefore, adjusting the depth to the halocline and inserting resistivities of a freshwater conduit cannot account for the observed anomaly.

If the depth to the halocline would be decreased by 10 m instead, the simulated background signal would be high (17.2 mS/m) (Table 7.4), but still within the measured range, yet it would still not be possible to obtain the anomaly value of 35 mS/m with this configuration. The deviation of the max. simulated signal using reasonable conduit conductivities to the max. anomaly value is 17 %.

If instead the depth to the halocline would be increased, this would only lower the values and it would still not be possible to obtain the measured anomaly values (results shown in Appendix J). Therefore, it is seen that adjusting the depth to the halocline cannot be used to explain the observed anomaly. Thus, the only other option is to adjust the resistivity of the saltwater layer.

**Table 7.4**. Experiments with varying the depth to the halocline and the effects of conduits in the geological configuration. As a proxy for a conduit present in the freshwater layer (Layer 2), the resistivity of Layer 2 is lowered to values between 10 and 50 Ohm-m. SW= saltwater. FW= freshwater.

ind 50 Onini-ini. 5 w Saitwater. 1 w	neshwater.
Simulated signal, $\sigma_a$ , using SW resistivity = 7 Ohm-m and depth to halocline: 50 m	<b>Simulated signal, </b> $\sigma_a$ , using SW resistivity = 7 Ohm-m and depth to halocline: 45 m
15.4 mS/m	17.2 mS/m
17.7 mS/m	19.3 mS/m
21.8 mS/m	23.0 mS/m
28.6 mS/m	29.2 mS/m
	Simulated signal, $\sigma_a$ , using SW resistivity = 7 Ohm-m and depth to halocline: 50 m 15.4 mS/m 21.8 mS/m 28.6 mS/m

In the sensitivity analysis, it has been found that the Vigia Chico Road geologic model is most sensitive towards changes in the resistivity of the saltwater zone. Therefore, the model is now calibrated with this parameter. Options for background configurations of the underground have been explored using different resistivities for the saltwater zone. Examples of results are seen in Figure 7.5 below.

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**Figure 7.5**. Options for different background configurations for the Vigia Chico Road measurement. The resistivities of the saltwater layer (Layer 3) have been varied to obtain the measured background values. The apparent conductivities of the configurations as found by Equation 3.2 are displayed under each model. SW= saltwater. Figure not to scale.

As seen, it is found that the saltwater zone is expected to have a resistivity between 5 and 11 Ohm-m to yield the observed background signals. These values correspond well with the values of about 4 to 15 Ohm-m found for the saltwater zone in an electrical resistivity study conducted in the area by Supper *et al.* (submitted), and the value of approx. 4 Ohm-m for the saltwater zone in the area reported by Rebolledo-Vieyra (pers. comm., 2006).

After having found the parameter values which fit to the background level, the effect of changing the resistivity of the freshwater layer is then investigated. The resistivity is lowered corresponding to the expected effect of the presence of a conduit. However, since it has been seen earlier (Table 7.3) that the midrange value for the saltwater resistivity – 7 Ohm-m – cannot yield the observed anomaly pattern, the lower value of 5 Ohm-m has to be used. This value still gives a background value which is below the signal values found for the anomalies. Furthermore, as seen in Table 7.5, this configuration yields a response that corresponds very well to the measured anomaly values<sup>9</sup>. The forward modelling of the Vigia Chico Road measurement thus suggests that the configuration used to make the data in Table 7.5 may be a valid geological model to explain the anomalies measured.

<sup>&</sup>lt;sup>9</sup> Attempts using the high background saltwater resistivity of 11 Ohm-m yields signals below 20 mS/m for reasonable FW conduit resistivities, wherefore this configuration cannot explain the observed anomalies. Details of these results can be seen in Appendix J.

	Simulated signal, $\sigma_a$ , using SW resistivity = 5 Ohm-m and depth to halocline: 55 m
FW resistivity = 50 Ohm-m	21.7 mS/m
FW resistivity = 20 Ohm-m	26.1 mS/m
FW resistivity = 15 Ohm-m	28.5 mS/m
FW resistivity = 10 Ohm-m	33.4 mS/m

**Table 7.5.** The effect of inserting a conduit in the configuration with saltwater (SW) resistivity of 5 Ohm-m. FW= freshwater.

#### 7.1.3 Discussion of Vigia Chico Road Model Results

According to the results shown in Table 7.5 conduit resistivities are found to be between 10 Ohm-m and 50 Ohm-m, if the anomaly measurements at the Vigia Chico Road do in fact indicate a conduit. These resistivities are found to correspond relatively well with values found by Supper *et al.* (submitted), who measured conduit resistivities of about 10-75 Ohm-m at Cenote Escondido, and of about 30-100 Ohm-m at Cenote Bomba.

The found values of conduit conductivity are however in the lower range. A reason for this could be that the thickness of the freshwater layer in this model also includes part of the mixing zone, since between the freshwater layer and the halocline there is a mixing layer. Since it is not possible to account for 4 layers in this 3-layer model, the middle layer of freshwater in the model could therefore include part of the mixing zone, which would lower the resistivity compared to if there was only freshwater present in the conduit.

Also if the conduit is actually so deep that it also contains some of the saltwater zone, it could explain why we have to use the lower value of the saltwater resistivity for modelling the anomalies compared to modelling the background values.

If one compares the conduit resistivity with what would be expected using Archie's Law (Equation 3.1) and typical values for freshwater conductivity and the parameters a and  $m^{-10}$  one obtains an apparent resistivity of the conduit of 6 Ohm-m. Our value is higher than this probably because the porosity is not 1 everywhere, since the conduit may not encompass the whole freshwater lens, so that some of the freshwater is in the matrix, and also because many conduits are decorated with speleothems which would also increase the resistivity.

Based on this forward modelling, the thickness of the freshwater zone is suggested to be 35 to 40 m (both thicknesses yield very similar responses), and these values correspond well with the general description of the freshwater lens thickness given by Villasuso & Méndes (1996, cited in CNA, 2001), who report that generally in the Yucatan Peninsula, thickness of the freshwater lens is in the order of 30 m 20 km

<sup>&</sup>lt;sup>10</sup> Conductivity of pure freshwater in the underground of Yucatán conduits may be up to 2.5 mS/cm according to Figure 3.11 in Beddows (2004) - equal to 4 Ohm-m. This relatively high conductivity is due to saturation with carbonate species. Typical values for the other parameters are: a = 1.5, m = 2. Moreover, in this example, the following values are used: n = 2, S = 1 (because we are dealing with the saturated zone, porosity = 1 (because we are looking at the case of a conduit, which is one large porespace, hence porosity is 1). The parameters *S* and porosity thus disappear from the equation of Archie's Law, since their values are 1.

from the coast, whereas further from the coast it may be 30 to 50 m thick. The thickness of the freshwater lens of the model also corresponds well with the thickness of the freshwater lens computed with the fitted analytical model from Chapter 4, which gives a freshwater lens thickness of 37-42 m.

Part of the Vigia Chico Road measurement has also been made using a coil spacing of 40 m, i.e. measurements where a greater part of the signal comes from deeper geological layers than the 20 m coil spacing data (data shown in Figure 7.2). This provided a possibility to support the proposed geologic model.

Forward modelling of the 40 m coil spacing response was found to yield the results shown in Table 7.6. The parameters "depth to halocline", "thickness of unsaturated zone" and "resistivity of dry limestone" are kept the same as found in the forward modelling of the 20 m coil spacing response.

**Table 7.6.** Establishment of the geologic parameters to yield the background signal measured with the 40 m coil spacing, as well as the effect of inserting a conduit in the configuration. SW= saltwater. FW= freshwater.

	8 8	
	<b>Simulated signal,σ</b> <sub>a</sub> , using SW resistivity = 5 Ohm-m	<b>Simulated signal,σ</b> <sub>a</sub> , using SW resistivity = 10 Ohm-m
	doing ow residency of onin m	doing ow residency 10 onin m
FW resistivity = 300 Ohm-m	36.6 mS/m	19.0 mS/m
(i.e. FW in matrix)		
FW resistivity = 20 Ohm-m	-	30.1 mS/m
(i.e. FW in conduit)		
FW resistivity = 15 Ohm-m	-	34.1 mS/m
(i.e. FW in conduit)		

As seen in Table 7.6 using the same saltwater resistivity as in the model for the 20 m coil spacing yielded a too high background response. Therefore, the resistivity of the saltwater layer was in this model increased to 10 Ohm-m. This yielded background values and anomaly values which correspond well with the measured signal. A possible physical explanation for that saltwater resistivity must be increased for the deeper measurement could be that the porosity of the limestone decreases with depth, so that the limestone would be more karstified in the upper parts. This would mean that when one measures to greater depths with this 40 m coil spacing, one has to adjust the saltwater resistivity upwards.

It would not be reasonable here to adjust the depth to the halocline, as it has to be the same depth as found when modelling the 20 m coil spacing response, since it is the same location.

If accepting such an adjustment of the saltwater resistivity, the model for the 40 m coil spacing response corresponds well with the measured signal and with the model parameters also used for the 20 m coil spacing. The background value for the 40 m coil spacing is modelled to be slightly higher than that of the 20 m coil spacing, which also is in agreement with the field measurements.

The modelling of the response of a 3-layered earth model supports the idea that the observed anomaly at Vigia Chico may arise from the presence of an underground freshwater conduit or a freshwater-carrying fracture.

# 7.2 The Holbox Fracture Measurement

#### 7.2.1 Location and Results of the Measurement

order to enhance the contrasts of the image. The red

An EM34 transect has been made along the Carrillo Puerto road north of Lake Kan-Luum, in an area which has been identified as being atop the Holbox Fracture zone (hereafter called the Holbox Fracture transect). However, this fracture zone is not sharply defined, since it consists of a belt of lineaments and/or fractures stretching from north-northeast to south-southwest. The Holbox Fracture zone can be seen on a topographical map, such as that displayed in Figure 7.6a. This topographical map is the SRTM map (USGS, 2004), which has been treated with a 'Hillshade' function in the ArcGIS software and histogram stretching in the ILWIS software to make topographical features more clearly visible. In Figure 7.6a, the fracture zone belt is marked by arrows, and the location of the measured transect is depicted with a red dot. The brown dots indicate structures identified on satellite images, which also correspond well with the Holbox Fracture zone.



dot indicates the measured Holbox Fracture transect. Brown dots are structures identified on satellite imagery. Blue areas are known open water bodies, data kindly provided by Amigos de Sian Ka'an. b) The measured transect on the Holbox Fracture zone (dark green and red line), displayed on an aerial photo from INEGI, kindly provided by CINDAQ. Red indicates the area where the believed anomaly is located. Figure 7.7 shows the results of the EM34 measurement on the Holbox Fracture transect. By visual inspection it seems that background values of apparent ground conductivity in the area is between about 9 and 15 mS/m. This is generally the same range as that found on the Vigia Chico Road transect, except that the Vigia Chico Road background signal was slightly higher at places. In two areas on Figure 7.7 values go above 15 mS/m, and thus seem to be anomalies. The first is about 60 m wide and is located about 990 m from the southern end of the transect. The second anomaly starts around 1870 m from the southern end of the transect. The second anomaly starts around 1870 m. The stretch has not been measured until background values were reached again due to time constraints and because it was known that the area continues into the area where the larger Ox Bel Ha cave system is known to be. Figure 7.6b shows a close up of the measured transect. It is known that there are caves located somewhat near to the measured transect on both sides of the transect. However, their location, extent and direction cannot be displayed here, because these data are not public domain and the authors do not have the rights to publish these particular cave line maps.



Holbox Fracture transect

Figure 7.7. Apparent conductivity measured with the EM34 along the Holbox Fracture transect.

#### 7.2.2 Modelling of the Results

Forward modelling is again initiated to analyze which ground configuration will lead to the observed signals, and whether this signal can be caused by the presence of underground conduits.

As previously, expected model parameter values for the location are obtained using literature values and measured values. As far possible it is attempted to use the same resistivities for the different materials as those used in the Vigia Chico Road forward modelling.

Again the resistivity of the unsaturated zone is fixed to 1000 Ohm-m, while the resistivity of the freshwater lens in the matrix is set to 300 Ohm-m. Table 7.7 depicts other values established for the Holbox Fracture location.

	0	0		
Distance from coast:	9	to	11	km
Ground elevation:	8	to	12	m above mean sea level
Expected depth to halocline:	30	to	33	m below mean sea level
Expected depth to halocline:	38	to	47	meters below ground surface (sum of the two above lines)
Expected thickness of unsaturated zone	10	to	20	m

Table 7.7. Parameter values used for the geologic model of the Holbox Fracture location.

As seen in Table 7.7, since this location is somewhat closer to the coast than the Vigia Chico Road site, this affects the expected depth to the halocline as well as the expected thickness of the unsaturated zone.

First, the background signal is modelled. Figure 7.8 below shows a configuration which is found to fit the background signal well. Again, the model is most sensitive to:

- the saltwater resistivity
- the depth to halocline

This is shown in Table 7.8, where the discrepancies are evaluated against the baseline model shown in Figure 7.8.



#### Apparent conductivity: $\sigma_a = 15.5 \text{ mS/m} \rightarrow \text{Acceptable background configuration}$

**Figure 7.8**. Acceptable model of the background geology for the Holbox Fracture transect. The apparent conductivity calculated with Equation 3.2 for this configuration is shown below the figure. Figure not to scale.

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Parameter varied		Simulated apparent conductivity ( $\sigma_a$ ) [mS/m]	Abs. change [mS/m]	% change
$\rho_1$	$\rho_1$ increased by 30%, value: 1300 Ohm-m	15.4	-0.1	-1%
	$\rho_1$ decreased by 30%, value: 700 Ohm-m	15.8	+0.3	+2 %
ρ <sub>2</sub>	$\rho_2$ increased by 30%, value: 390 Ohm-m	15.4	-0.1	-1%
	$\rho_2$ decreased by 30%, value: 210 Ohm-m	15.8	+0.3	+2 %
ρ <sub>3</sub>	$\rho_3$ increased by 30%, value: 9 Ohm-m	12.3	-3.2	- 21 %
	$P_3$ decreased by 30%, value: 5 Ohm-m	21.6	+6.1	+39 %
Depth of unsaturated	10 m increase in depth, value: 25 m	15.3	-0.2	+2%
zone	10 m decrease in depth, value: 5 m	16.3	+0.8	+5 %
Depth to halocline	10 m increase in depth, value: 60 m	13.3	-2.2	-14 %
	10 m decrease in depth, value: 40 m	18.9	+3.4	+22 %
	5 m increase in depth, value: 55 m	14.3	-1.2	-8 %
	5 m decrease in depth, value: 45 m	17.0	+1.5	+ 9 %

Table 7.8.	Sensitivity	of simulate	ed signal to	change in e	ach model	parameter.	All changes	are relative to	o the
baseline va	alue of 15.5	5 mS/m give	en in Figure	7.8. Locali	tv: Holbox	Fracture ze	one.		

However, the configuration in Figure 7.8 is not the only possible background configuration. Various saltwater resistivities have been found to yield acceptable background values. These can be seen in Table 7.9.

As seen from the table, using a saltwater resistivity of 5 Ohm-m, as used in the Vigia Chico Road model for the anomaly zone, yields a background signal which is too high. A saltwater resistivity of 7 Ohm-m to 12 Ohm-m yields a better response with values in the range of the measured background signal, so these settings are regarded as settings for the background values.

Table 7.9. Determination of the saltwater (SW) resistivity which yields acceptable background value
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corresponding to those measured. FW = freshwater. Shading indicates too high signal for a background value.					
σa	SW resistivity				
	= 5 Ohm-m	= 6 Ohm-m	= 7 Ohm-m	= 10 Ohm-m	= 12 Ohm-m
FW resistivity = 300 Ohm-m	21.2 mS/m	17.9 mS/m	15.5 mS/m	11.3 mS/m	9.6 mS/m
(i.e. FW in matrix)					

Two different geological model configurations are now used to model the measured anomaly responses of between 15 and 23 mS/m. A middle background saltwater resistivity of 10 Ohm-m is chosen, along with the lowest background saltwater resistivity of 7 Ohm-m. Table 7.10 shows the result.

neshwater. Shading indicates too low signal for an anomary.				
SW resistivity = 10 Ohm-m		SW resistivity = 7 Ohm-m		
	σa		σa	
FW resistivity = 50 Ohm-m	14.7 mS/m	FW resistivity = 50 Ohm-m	18.9 mS/m	
(i.e. conduit)		(i.e. conduit)		
FW resistivity = 20 Ohm-m	20.8 mS/m	FW resistivity = 30 Ohm-m	21.6 mS/m	
(i.e. conduit)		(i.e. conduit)		
FW resistivity = 15 Ohm-m	24.2 mS/m	FW resistivity = $20 \text{ Ohm-m}$	25.0 mS/m	
(i.e. conduit)		(i.e. conduit)		

**Table 7.10**. The effect of inserting a conduit in the configuration with saltwater (SW) resistivity of 5 Ohm-m. FW= freshwater. Shading indicates too low signal for an anomaly.

However, it is necessary to also investigate whether the depth to the halocline should be adjusted instead of the resistivity of the saltwater zone. Therefore, an attempt is made to fit the model to the background values using the saltwater resistivity obtained at the Vigia Chico Road anomaly, namely 5 Ohm-m. Table 7.11 displays the results. As seen, it is not possible to obtain the measured background values with neither a 5 m nor a 10 m increase in the depth to the halocline. It has been found that the depth to the halocline has to be 75 to 120 m below surface in order to yield the measured background values of 15 to 9 mS/m, respectively. Such large depths to the halocline at a site only 9 to 11 km from the coast are not realistic. Therefore, changing the depth to the halocline will not be able to explain the measured signal at the Holbox Fracture Zone transect, if reasonable resistivity values should be used. The case of 7 Ohm-m saltwater resistivity and the depth to the halocline of 50 m thus is the only reasonable 3-layer configuration for this site.

**Table 7.11**. Effect of changing depth to the halocline to obtain background values while maintaining the saltwater (SW) resistivity used at the Vigia Chico anomaly. The values are higher than the measured background level of 9-15 mS/m.

	Simulated signal, $\sigma_a$ , using SW resistivity = 5 Ohm-m and depth to halocline: 55 m	Simulated signal, $\sigma_a$ , using SW resistivity = 5 Ohm-m and depth to halocline: 60 m
FW resistivity = 300 Ohm-m	19.4 mS/m	18.0 mS/m

#### 7.2.3 Discussion of Holbox Fracture Model Results

Due to equivalence the two models types described in Table 7.10 both seem to capture the measured signal of the anomalies using reasonable model parameter values. When using a saltwater resistivity of 10 Ohm-m it is seen that the results indicates that the resistivity of a freshwater conduit should be between 15 and 20 Ohm-m, i.e. in the lower range of the values found by Supper *et al.* (submitted) but still acceptable. Also, this configuration would mean that the difference between the resistivity of the saltwater and the freshwater in the conduit would only be 5 Ohm-m. On the other hand, if a saltwater resistivity of 7 Ohm-m is used, the background value would be in the higher range, but this value would correspond better to the saltwater resistivity used also for the Vigia Chico Road background modelling, and furthermore it would yield freshwater conduit resistivities between 20 Ohm-m and 50 Ohm-m which correspond well with the findings of Supper *et al.* (submitted). Also, this latter case yields a greater difference between the resistivity of the saltwater and the freshwater in the conduit resistivities between 10 Ohm-m and 50 Ohm-m which correspond well with the findings of Supper *et al.* (submitted). Also, this latter case yields a greater difference between the resistivity of the saltwater and the freshwater in the conduit.

The thickness of the freshwater lens in the model of about  $\sim 35$  m also here corresponds rather well with that found with the fitted analytical model from Chapter 4, which predicts a freshwater lens thickness of 30 to 33 m at this distance from the coast.

In general, there is a good agreement between the resistivities of the models for the two different locations, as seen from Figure 7.9. However, the model of the Holbox Fracture zone transect has slightly higher values for the freshwater conduit resistivity, which is however in better agreement with the results from Supper *et al.* (submitted). A background saltwater resistivity of 7 Ohm-m was found to describe the data well at both locations. However, at the Vigia Chico Road, it has been necessary to apply a slightly lower saltwater resistivity at the anomaly. This may be explained by a greater volume of saltwater being present in the conduit at this location.



**Figure 7.9.** Results of the Vigia Chico Road model and the Holbox Fracture Zone model compared. Shading indicates the conduit which is assumed to cause the anomaly. Not to scale.

# 7.3 The Caapechen Measurement

#### 7.3.1 Location and Results of the Measurement

Two EM34 transects have been made in the brackish Caapechen lagoon in the Sian Ka'an Biosphere Reserve to investigate the Caapechen cave system. One transect has been made over known cave line (in the following called Caapechen South) and one has been made near the end of the - at that time - surveyed stretch of the Caapechen line, in order to investigate the direction that the cave would take (in the following called Caapechen North) (locations displayed in Figure 7.2 and Figure 7.10). The area in general is hard to access. Thus, Caapechen South has been made over water, using plastic kayaks for holding and moving the equipment. Caapechen North has been made on a small sandy/silty strip island covered with mangrove trees.

In the Caapechen transects the first (upper) layer of the general geologic model is thus brackish water and not unsaturated limestone as seen at the other locations.



**Figure 7.10.** Location of the Caapechen EM34 measurements. Cave line map (yellow line) courtesy of the Mexico Cave Exploration Project and CINDAQ. Principal explorers of the cave system are F. Attolini, A. Alvarez, R. Chavez Arce, F. Devos, J. Jablonski, C. Le Maillot. L. Magheli, A. Marassich, D. Riordan, G. Rocca, P. Thomsen, M. Valotta. Background image: Landsat ETM+.

In this survey the coil spacing used is 10 m, because when attempting to use larger coil spacings, readings were too high for the instruments to show, i.e. they were larger than 300 mS/m. This is caused by the background environment of brackish water.

The EM34, as well as other geophysical equipment which measures electrical conductivity or resistivity, does not function well in such a brackish environment, and apparent anomalies may not be caused by e.g.

the presence of conduits but instead may be an effect of changes in porosity. This will be examined further in the following, by forward modelling of the measured Caapechen response.

Before modelling is initiated it is important to get an idea of the electrical conductivity of the brackish lagoon water which forms the upper layer of the geological model at this location. The electrical conductivity of the brackish lagoon water has been measured to be 3250 mS/m, equivalent to 0.31 Ohm-m. This value fits well with it being a mix of freshwater and sea water, since Telford *et al.* (1990) reports freshwater resistivities to range between 0.5-150 Ohm-m (1-100 Ohm-m for natural waters in sediments) and seawater resistivities as 0.2 Ohm-m. We measured a seawater value within this range in the Caribbean Sea, namely 5340 mS/m, i.e. 0.19 Ohm-m.

Using Archie's Law (Equation 3.1) we can get an idea of the expected apparent resistivity of the upper layer of lagoon water, as displayed in Table 7.12. As seen, the upper layer of lagoon water is expected to have an apparent resistivity between 0.5 and 6.7 Ohm-m. For these calculations *S* (the fraction of pores containing water) has been set to 1 (saturated zone). In addition, different values of the porosity have been used. The values have been set based on field observations that the sediment in the area mainly consists of medium to fine sand, silt and clay, with most of the material in the finer section. Tabulated values in Sonnenborg *et al.* (2001) show that average porosity values for clay, silt, fine and medium sand are 0.42, 0.46, 0.43 and 0.39, respectively, while these the lowest porosity of these sediment types is 0.26 (silt) and the highest is 0.7 (clay).

	<i>S</i> = 1	Comment
	Calculated resistivity	-
	[Ohm-m]	
With typical values	2.8	Typical values for <i>a</i> and <i>m</i> : $a=1.5$ , $m=2$ ,
		average porosity= 0.4
With lowest <i>a</i> and <i>m</i> values	0.5	Lowest <i>a</i> and <i>m</i> values: $a= 0.5$ , $m=1.3$ ,
		average porosity= 0.4
With highest <i>a</i> and <i>m</i>	7.4	Highest <i>a</i> and <i>m</i> values: <i>a</i> = 2.5, <i>m</i> =2.5,
values		average porosity= 0.4
With lowest porosity	6.7	Typical values for a and <i>m</i> ,
		Lower limit of porosity = 0.26
With highest porosity	0.9	Typical values for <i>a</i> and <i>m</i> ,
		Upper limit of porosity $= 0.7$

 Table 7.12. Resistivities calculated based on Archie's Law (Equation 3.1) and the lagoon water conductivity of approx. 0.3 Ohm-m.

7 – Analysis of Structures with Geophysical Methods



Figure 7.11. Apparent conductivity measured with the EM34 along the Caapechen South transect (left) and the Caapechen North transect (right).

Figure 7.11 displays the results of the EM34 measurements over the mentioned transects, and Figure 7.12 shows a close-up of the location of the transects relative to the surveyed cave. As seen, the survey made over known cave (Caapechen South, Figure 7.11(left) and 7.12a) did unfortunately not detect the cave. The reason for this will be investigated in the modelling section. However, the figure with results from Caapechen South reveals that the background level of apparent resistivity using 10 m coil spacing seems to be between 240 and 270 mS/m.

This is useful to keep in mind when viewing the Caapechen North results. Here, the background level seems to be in the same range; however one or two anomalies seem to be present. The location of the larger anomaly is marked with red dots on Figure 7.12b while the location of the smaller anomaly is marked with pink dots. As seen in Figure 7.12b the location of the largest anomaly could seem to be in continuation of the end of the currently surveyed line of the Caapechen. The anomalies detected in this case have *lower* values than the background level.



**Figure 7.12.** a) The Caapechen South transect, which was measured over known cave over water. Dots (measurement points) are all blue, indicating no detected anomalies. Yellow line displays currently explored cave. Line map depicts direction of cave, but not width of cave. b) The Caapechen North transect. Red dots indicate the location of an area with generally lower values (180-200 mS/m) than background, while pink dots indicate the location of an area with somewhat lower values (200 mS/m). The transect bends due to the shape of the strip island that the measurement was conducted on. Yellow line displays currently explored cave. Line map depicts direction of cave, but not width of cave. Cave line map courtesy of the Mexico Cave Exploration Project and CINDAQ. Principal explorers of the cave system are F. Attolini, A. Alvarez, R. Chavez Arce, F. Devos, J. Jablonski, C. Le Maillot. L. Magheli, A. Marassich, D. Riordan, G. Rocca, P. Thomsen, M. Valotta. Background image: Landsat ETM+. Pixel size: 30 m. x 30 m

In general, the measured values of apparent conductivity at the Caapechen transects ranged from 180 mS/m to about 270 mS/m (as seen in Figure 7.11). An anomaly caused by the presence of a conduit in such an environment could either be *higher* than the background, if the normal pattern is expected, where there is a freshwater lens between the upper brackish layer and the lower saline layer (Normal Case). However, in some instances conduits yield a *lower* signal than the background values, which would then be because freshwater would only be present in the conduit, and in the matrix surrounding the conduit there would only be brackish or saline water (Inverse Case). This has been seen when conducting EM34 measurements near the coast on the beach (own measurements and unpublished results from Supper *et al.* (submitted)). In the following, both the Normal Case and the Inverse Case will be investigated, with the latter first. A sensitivity analysis of the Caapechen model will be presented under the Normal Case.

#### 7.3.2 Modelling and Discussion of the Results

#### 7.3.2.1 Inverse Case

Looking at Figure 7.11 and the maps of the anomaly in relation to the conduit (Figure 7.12), it would seem like the depressions in the signals (values 180 mS/m to 200 mS/m) could indeed indicate the presence of a conduit, judging from their location in relation to the explored caves as well as the width of the seemingly anomalies. This would mean that the Inverse Case would be applicable to the data.

However, it does not seem physically likely that there should not be a freshwater lens in this area, which is located 3-4 km from the coast. Yet, to investigate this possibility of the Inverse Case, forward

modelling of this scenario was undertaken. The values used to fix thicknesses of layers etc. are shown in Table 7.13. Regarding the depth to the halocline, it should be noted that field observations from divers exploring the Caapechen cave system have shown that depth to the halocline in this particular cave system seems to drop more rapidly than in other cave systems. Thus, according to Le Maillot (pers. comm., 2006) the halocline at the cave entrance is at 14 m.b.s.l, falling to 17 m.b.s.l. a little further in, and dropping down to 19 m.b.s.l. only 550 meters inland from the entrance. Such a drop in depth to the halocline of 5 meters over 550 m conduit cannot be predicted by the fitted analytical model used in this report for estimating the depth to the halocline, since this model only predicts a drop of about 2 m for such a stretch. As yet, no explanation has been found for this abnormal pattern in the Caapechen system. Here, the forward modelling will however be undertaken using the fitted analytical model from Chapter 4 for estimating the halocline depth, to ensure consistency between the various EM34 modelling efforts, and because the average depth to the halocline calculated by this model is equal to that reported by Le Maillot (19 m.b.s.l.) (pers. comm., 2006).

Table 7.13. Parameter values used for the geologic model of the Caapechen location.

Distance from coast:	3	to	4	km
Ground elevation:	-1	to	2	m above mean sea level
Expected depth to halocline:	18	to	20	m below mean sea level
Expected depth to halocline:	17	to	22	meters below ground surface (sum of the two above lines)
Expected thickness of brackish water zone	0	to	1-2	m according to field observations

Selected results from the modelling are displayed in the Figure 7.13 and Table 7.14. It is seen that if a background value between 240 and 260 mS/m should be obtained in this scenario which has no freshwater lens, the resistivity of the brackish water (Layer 1) has to be in the higher range of about 4 Ohm-m (Figure 7.13). Lower values yielded too high background signals.



Apparent conductivity:  $\sigma_a = 244 \text{ mS/m} \rightarrow \text{Acceptable background configuration}$ 

Figure 7.13. Values used for modelling the background signal, in the case of no freshwater lens at Caapechen (Inverse Case).

According to Le Maillot (pers. comm., 2006) the dimensions of the caves at Caapechen are about 8-12 m from ceiling to bottom near the end of the line. The bottom of the cave was located at 19 m depth at the end of the line, but generally varies from 19 m depth to 21 m depth in that area. The dimensions of the cave was now inserted, while maintaining the depth to the halocline at 21 m below ground surface and assuming that the bottom of the cave is located at the halocline. Using reasonable values for freshwater conduit resistivity in this configuration yields the results shown in Table 7.14. It is seen that for this scenario it is not possible to obtain as low values as 180 mS/m to 200 mS/m which were the values of the anomalies. The lowest apparent resistivity of the media this configuration can yield is 209 mS/m, when an unrealistic high resistivity of 1000 Ohm-m is used for the freshwater conduit and conduit height is 12 m (data in Appendix J). Only if a higher brackish water resistivity of e.g. 5 Ohm-m is used do values

reach 175-190 mS/m if a freshwater conduit is modelled, but then too low a background value is obtained (200 mS/m) (data in Appendix J). Thus, the forward modelling cannot confirm the idea that the observed lower value anomalies are in this location caused by presence of freshwater conduits in an environment where the surrounding matrix does not have a freshwater lens.

**Table 7.14**. Experiments with inserting a conduit of varying dimensions and with different freshwater (FW) resistivity in the configuration where no freshwater lens is present in the surrounding matrix.

σ <sub>a</sub>	With FW conduit 8 m high	With FW conduit 11 m high	With FW conduit 12 m high
FW resistivity = 50 Ohm-m	228 mS/m	217 mS/m	212 mS/m
(i.e. conduit)			
FW resistivity =	230 mS/m	220 mS/m	216 mS/m
20 Ohm-m			
(i.e. conduit)			

#### 7.3.2.2 Normal Case

Since the Inverse Case has now been rejected, the likelihood of detecting a conduit in the Normal Case in the Caapechen brackish environment will now be explored.

The parameters presented in Table 7.13 above are the same for the Normal Case also.

First, the parameters to yield the observed background values were explored. A reasonable background configuration is presented in Figure 7.14. Thickness of the upper layer with brackish water is set to 2 m, and the background signal obtained with this model is 241 mS/m.



Apparent conductivity:  $\sigma_a = 241 \text{ mS/m} \rightarrow \text{Acceptable background configuration}$ 

**Figure 7.14**. Acceptable model of the background geology at the Caapechen transect. The apparent conductivity calculated with Equation 3.2 for this configuration is shown below the figure. Figure not to scale.

The results of a sensitivity analysis are displayed in Table 7.15. The discrepancies are relative to the configuration shown in Figure 7.14. The models were found to be most sensitive to:

- the brackish water resistivity
- the depth of the brackish water zone

As a result of the sensitivity analysis, the brackish water resistivity may be varied in order to obtain the range of measured values at the Caapechen transects. This has been explored and results are presented in Table 7.16.

Parameter varied		Simulated apparent conductivity (ơa) [mS/m]	Abs. change [mS/m]	% change
$\rho_1$	$\rho_1$ increased by 30%, value: 1.95 Ohm-m	191	-50	-21 %
	$\rho_1$ decreased by 30%, value: 1.05 Ohm-m	333	+92	+38 %
ρ <sub>2</sub>	$\rho_2$ increased by 30%, value: 390 Ohm-m	240	-0.4	0 %
	$\rho_2$ decreased by 30%, value: 210 Ohm-m	242	+ 1	0 %
ρ <sub>3</sub>	$\rho_3$ increased by 30%, value: 9 Ohm-m	235	- 5	- 2%
	$P_3$ decreased by 30%, value: 5 Ohm-m	251	+10	+ 4 %
Depth of brackish	5 m increase in depth, value: 7 m	477	+236	+98%
water zone	0.5 m decrease in depth, value: 1.5 m	196	-45	- 19 %
Depth to halocline	10 m increase in depth, value: 31 m	233	- 7	- 3%
	10 m decrease in depth, value: 11 m	260	+19	+ 8%
	5 m increase in depth, value: 26 m	236	- 4	- 2%
	5 m decrease in depth, value: 16 m	248	+ 7	+ 3 %

**Table 7.15**. Sensitivity of simulated signal to change in each model parameter. All changes are relative to the baseline value of 241 mS/m shown in Figure 7.14. Locality: Caapechen transect.

Equivalent porosity using typical values for <i>a</i> and <i>m</i> in Archie's Law (see Table 7.12)	0.7	0.59	0.55	0.48	0.4
σ <sub>a</sub>	Brackish water resistivity = 0.9 Ohm-m	Brackish water resistivity = 1.3 Ohm-m	Brackish water resistivity = 1.5 Ohm-m	Brackish water resistivity = 2 Ohm-m	Brackish water resistivity = 2.8 Ohm-m
FW resistivity = 300 Ohm-m (i.e. FW in matrix)	384 mS/m	274 mS/m	241 mS/m	187 mS/m	141 mS/m

In the modelling, it was chosen to keep the saltwater resistivity at 5 Ohm-m as the modelling of the Vigia Chico Road anomaly had shown. As seen in the sensitivity analysis, it would not make a significant difference if values of 7 Ohm-m or 10 Ohm-m (background saltwater resistivities found at Holbox Fracure Zone transect) would be used. Thus, only the brackish water resistivity was varied to obtain values in the range of the measured apparent conductivities.

As seen in Table 7.16, using the resistivities of 2.8 Ohm-m for the brackish water, corresponding to an average porosity of 0.4 with typical values for a and m in Archie's Law (Table 7.12) yields too low a value, while using the maximum porosity of 0.7 giving a resistivity of 0.9 Ohm-m yields too large a signal. However, the resistivities between these extremes are seen to yield apparent conductivities in the same range as those measured. As seen, these values correspond to porosities of between 0.48 and 0.59, and it is thus obvious that small changes in the porosity of the geologic medium over the measured transect would easily be able to explain the variation in the measured signal, so that the anomalies would be caused by this change in porosity. Porosity changes are not unlikely over the transect since there can be local variations in the sediments' composition of grain size and level of compaction.

It is now investigated what influence the presence of a conduit in such an environment would have on the apparent conductivity. Table 7.17 displays selected results using 2 different values for the resistivity of the freshwater conduit, and the highest reasonable resistivities of the brackish water layer, as found above.

Equivalent porosity using typical values for <i>a</i> and	0.48
<i>m</i> in Archie's Law (see Table 7.12)	
σ <sub>a</sub>	Highest brackish
	water resistivity
	= 2 Ohm-m
Background value	187 mS/m
(with FW resistivity = 300 Ohm-m)	
FW resistivity = 50 Ohm-m	196 mS/m
(i.e. FW in conduit)	
FW resistivity = 20 Ohm-m	213 mS/m
(i.e. FW in conduit)	

 Table 7.17. Effect of inserting conduit into one of the geologic model configurations found acceptable for the site.

 Equivalent porosity using typical values for *a* and
 0.48

It is seen that the effect of inserting a conduit would be an increase in the measured apparent conductivity of 10-15 mS/m, i.e. only a slight increase. However, as is shown in Table 7.18, a similar increase could be obtained if, instead of inserting a conduit, the porosity is increased by 0.01 to 0.04, i.e. a relatively small porosity change.

**Table 7.18.** Effect of changing the porosity, and thus the brackish water resistivity, in Layer 1 while using the configuration without a conduit.

Equivalent porosity using typical values for a and	0.52	0.49
<i>m</i> in Archie's Law (see Table 7.12)		
σa	Brackish water	Brackish water
	resistivity	resistivity
	= 1.7 Ohm-m	= 1.9 Ohm-m
FW resistivity = 300 Ohm-m	215 mS/m	195 mS/m
(i.e. FW in matrix)		

Alternatively, the depth of the brackish water should be varied in order to obtain the range of measured values at the Caapechen transect, as seen from the sensitivity analysis.

The brackish water zone cannot be much more than 2 m deep, since the topographical relief at the site is  $\sim$ 0-2 m.a.s.l., and the freshwater head must be above sea level. On the other hand the brackish water

layer is not evaluated to be much shallower than 1.5 m, since this is evaluated to be the average depth of the lagoon at the Caapechen measurement sites. If comparing with the result of using the fitted analytical model from Chapter 4, the height of the fresh groundwater table,  $h \approx 0.5$  m.a.s.l, which would give a thickness of the first (brackish) layer of about 1-1.5 m, depending on the ground elevation. The field observations are thus trusted more than the fitted model, but they only deviate from each other by ~0.5 m.

Results from having a brackish water zone of 1.5 m depth and the effect of a conduit in such an environment is seen in Table 7.19. It is seen that the background value is lower, but still acceptable, with this configuration compared to that of Figure 7.14, and the effect of inserting a conduit is an increase in the apparent conductivity of 10-30 mS/m, i.e. again a relatively small increase. As shown in Table 7.20 again a similar increase could be obtained if instead of inserting a conduit, the porosity of the brackish layer is increased by 0.01-0.04, i.e. a relatively small porosity change.

**Table 7.19.** Effect of inserting conduit into one of the geologic model configurations found acceptable for the site, with a minimum thickness of the brackish water zone applied, i.e. 1.5 m.

with a minimum theckness of the brackish water zo	ne applieu, i.e. 1.5 m.
Equivalent porosity using typical values for <i>a</i> and <i>m</i> in Archie's Law (see Table 7.12)	0.55
σa	Brackish water resistivity
	= 1.5 Ohm-m
	With lowered thickness of brackish
	water zone, i.e. now 1.5 m
Background value	196 mS/m
(with FW resistivity = 300 Ohm-m)	
FW resistivity = 50 Ohm-m	207 mS/m
(i.e. FW in conduit)	
FW resistivity = 20 Ohm-m	225 mS/m
(i.e. FW in conduit)	

**Table 7.20.** Effect of changing the porosity, and thus the brackish water resistivity, in Layer 1 while using the configuration without a conduit.

Equivalent porosity using typical values for <i>a</i> and	0.59	0.56
m in Archie's Law (see Table 7.12)		
σ <sub>a</sub>	Brackish water	Brackish water
	resistivity	resistivity
	= 1.3 Ohm-m	= 1.4 Ohm-m
FW resistivity = 300 Ohm-m	222 mS/m	208 mS/m
(i.e. FW in matrix)		

Thus, the measured anomalies are not likely to be caused by measuring the presence of a conduit, but are more likely to be caused by variation in porosity. Also variation in the fraction of pores containing water (the S parameter in Archie's Law) and variation in the a and m parameters in Archie's Law could be the reason for the observed anomalies. This does not mean that there cannot be conduits beneath the transects, but their presence cannot be verified with geophysical equipment which measures electrical resistivities of the underground.

It is also seen from the modelling that a conduit would only increase the signal slightly, and may therefore be masked by small variations in the geology. This is probably the reason why no anomaly was measured above the known cave at Caapechen South.

The EM34 measurements over the Caapechen transects have thus shown that this method is not useful for detecting freshwater conduits in brackish water environments, and it has been made clear that although the measured signal at a first glance could look like anomalies caused by conduits, it is in fact not possible to say so based on the measurements.

# 7.4 Conclusions on the Electromagnetic Measurements and the Modelling of the Signals

The following conclusions can be made based on the above analysis of the measured EM34 signals:

- The forward modelling of the Vigia Chico Road and the Holbox Fracture Zone transects supports the belief that the anomalies detected by EM34 do indeed indicate the presence of underground conduits or, alternatively, freshwater-bearing fractures.
- The forward modelling of the Caapechen transect cannot confirm the presence of conduits under the measured stretch.

Since presence of conduits under the Vigia Chico Road transect has been supported by the forward modelling, this gives an interesting aspect. The Vigia Chico Road transect was namely, as mentioned, selected based on the identification of structures on satellite imagery. So this supports that it may be possible to use the identified structures for delineating zones of increased hydraulic permeability. However, only one measurement has been made above the identified structures. Having a few more measurements would have helped support the use of the satellite-structure approach. Yet, given the lack of data in especially the southern and western part of the model area regarding location of conduits, the satellite-structure approach offers a first order estimate of the location of these zones, and they will therefore be used in the first setup of a regional hydrological model of the area. For the future, other of the identified structures should be investigated further, to confirm or reject the hypothesis that they are all related to zones of higher hydraulic permeability.

The Holbox Fracture zone location was chosen based on that a measurement on the Holbox Fracture zone was wanted, and this location was one of the only accessible spots. Furthermore, it was seemingly in line with Lake Kan-Luum and other lakes north of this. However, this area was *not* identified as a structure on the satellite image. The measurement on the Holbox Fracture zone shows that in this zone there is not a generally higher permeability everywhere. Instead, there seems to be zones with conduit development or freshwater-bearing fractures in the underground and zones without, even on a transect that crosses over the Holbox fracture zone. Similar results were found by Steinich & Marin (1996) who used resistivity surveys to investigate the large structure of the Chicxulub Impact Crater in the Yucatan State. Also this structure was found to have zones of higher permeability and zones of lower permeability and is thus not a continuous structure of higher permeability (Steinich & Marin, 1996). However, it is believed that, as in the case of the Chicxulub structure, the Holbox Fracture zones has a general large impact on the *regional* groundwater pattern dispite possible patches of discontiunuty so that the Holbox Fracture zone should still be inserted as a high permeability zone in the regional hydrological model.

In addition, cave maps have also showed that there are caves on both sides of the measured Holbox Fracture zone transect, and therefore, the measured transect cannot be interpreted as a definite boundary between areas of cave development and areas of no cave development.

The results from Caapechen have shown that in a brackish water environment, the electromagnetic method is generally not capable of detecting underground conduits, since observed anomalies may just as well be caused by small changes in the geology.

# NUMERICAL HYDROLOGICAL MODELLING

# NUMERICAL HYDROLOGICAL MODELLING

In order to manage the water resources of the model area properly there is a need to understand how the hydrological system of the area functions and how the matrix and high-permeability compartments interact. If this knowledge is obtained, it provides information which is crucial for evaluating the size of the groundwater resource and for evaluating the spread of groundwater pollutions in space and time.

The hydrological modelling should be done on two different scales – regionally and locally. A regional model is important in order to study the system on an overall level. Subsequently, smaller areas of special interest may be sliced out of the regional model and be modelled with a higher degree of detail.

The knowledge obtained in the previous sections on Aquifer State and Aquifer Structure is combined and included in the numerical hydrological modelling to obtain a description of the aquifer state based on the aquifer structure.

In general, there are four main analytical approaches for hydrological flow modelling in karst systems:

<u>The lumped modelling approach</u> does not take spatial distribution into account, but basically tries to describe the spring response of a karst aquifer to recharge on a regional scale (e.g. Dreiss, 1989; Felton & Currens, 1994; Bonacci & Živaljević, 1993).

<u>The equivalent porous medium approach</u> assumes the karst aquifer to be dominated by matrix flow, and if conduit flow is taken into consideration, this is done by ascribing higher permeability to the areas where they are presumed located, while flow is however still described here as laminar (e.g. González-Herrera *et al.*, 2002; Laroque *et al.*, 1999; Scanlon *et al.*, 2003).

<u>The conduit modelling approach</u> simulates flow in a karst aquifer as flow through a network of connected pipes (e.g. Jeannin, 2001; Springer, 2004; Halihan & Wicks, 1998).

<u>The conduit-matrix (dual permeability) modelling approach</u> is basically that flow is simulated in a fissured matrix, represented as an equivalent porous medium, and in a conduit network, while ensuring that in the model there is an exchange of water between these two compartments (e.g. Cornaton & Perrochet, 2002; Arfib & de Marsily, 2004). Thus, it is a combination of the latter two aforementioned approaches, but with the important additional aspect of inter-compartment exchange.

In the pre-thesis it was found that the conduit-matrix modelling approach is the most accurate for describing the current conceptual understanding of karst aquifers. As suggested in the pre-thesis, the applicability of using a combination of the modelling systems MIKE SHE and MOUSE (DHI, 2005b) for a karst conduit-matrix model will be investigated in the following. The other alternative, besides writing our own code, could be to use MODFLOW (Harbaugh *et al.*, 2000) and the newly developed module for karst system MODFLOW-DCM (South West Research Institute, 2006). However, this code was not available at the time of this project, and therefore could not be tested.

A conduit-matrix model is more computationally intensive than an equivalent porous medium (EPM) model. Therefore, for regional-scale modelling it may be necessary to use EPM modelling instead, and the implications of this will be investigated in the following chapter.

The regional-scale model will be founded upon the simple regional-scale equivalent porous medium model which was developed in the pre-thesis. When developing the regional-scale model as an equivalent porous medium model the system is thus conceptualized differently on a local scale and on a regional scale, providing a simplification of the flow regimes on the regional scale due to the large scale perspective.

The following chapters first present a simple conduit-matrix model and discuss the implications of using such a model for modelling the model area. Subsequently, a regional equivalent porous medium model is presented. The models have been created using MIKE SHE Version 2005, with Service Pack 4 and MOUSE Version 2005, Service Pack 1 (DHI, 2005b).

# 8 Simple Generic Conduit-Matrix Model

## 8.1 Purpose

The aims of conducting simulations with a simple generic conduit-matrix model are the following:

- To investigate, whether a coupling of MIKE SHE and MOUSE is applicable for modelling karst aquifer systems in general and the Yucatan Caribbean aquifer in particular.
- To investigate which model parameters have a great influence on the results of the simple conduit-matrix model and which parameters have less impact on the model output, i.e. to perform a sensitivity analysis by varying the parameters which are not well known in the model.
- To investigate the order of magnitude of the hydraulic conductivity of structures/conduits, if they are to be modelled with an equivalent porous medium model instead of a conduit/matrix model. This will be done by comparing the outputs of a conduit-matrix model and a similar model setup using an equivalent porous medium model description.
- To investigate the computational costs of running a conduit-matrix model (with MIKE SHE and MOUSE) compared to an equivalent porous medium model (with MIKE SHE).

The following sections of this chapter address these purposes in the order mentioned above. In addition, the conceptual background and setup of the simple conduit-matrix model are presented.

# 8.2 Applicability of MIKE SHE/MOUSE for Conduit-Matrix Modelling

To assess the applicability of the MIKE SHE/MOUSE coupling for conduit-matrix modelling of karstic aquifer we must both consider how well the software describes our conceptual understanding of the systems, and also how computationally intensive this type of model is. In the present section, the first question will be addressed, while the latter aspect will be addressed in Section 8.10.

As discussed in the pre-thesis the MOUSE software models conduit flow by using a 1D formulation of the Saint Venant equations. The Saint Venant equations are presented in Appendix P. Generally, the mathematical descriptions of the conduit flow in MOUSE are well suited for our purpose.

Here, we will only in detail repeat the way MOUSE is coupled to the MIKE SHE component, since this is essential for the conceptual understanding of the karst aquifer system that we use here and for the conduit-matrix model type.

The coupling between MIKE SHE and MOUSE takes place between the MIKE SHE grid cells and the MOUSE "links" (i.e. conduit sections) which are located in each cell. This coupling is controlled by the head difference between conduit heads and aquifer heads in the cell and a leakage coefficient. The leakage coefficient is defined as the hydraulic conductivity of the conduit wall divided by the conduit

wall thickness. In analogy with Darcy's Law, the exchange flow between saturated zone and MOUSE link is thus described by (DHI, 2005a):

$$Q_{SZ-MOUSE} = \Delta H \cdot L_c \cdot R_H \cdot Length$$
 (Eq. 8.1)

where  $Q_{SZ-MOUSE}$  is the exchange flow between the saturated zone and the MOUSE link [L<sup>3</sup>/T],  $\Delta H$  is the head difference between aquifer and conduit [L],  $L_c$  is the leakage coefficient [1/T] (conductance pr. unit wetted perimeter pr. unit length),  $R_H$  is the hydraulic radius [L] and *Length* is the length of the MOUSE link [L]. There are two options in MOUSE for describing the leakage coefficient in this type of exchange coupling. One is where only the leakage coefficient of the conduit is taken into consideration; the other is where a harmonic mean of the conduit's leakage coefficient and the aquifer's leakage coefficient is used. The aquifer's leakage coefficient is here calculated as an average leakage coefficient of the specific aquifer grid cell, while assuming that the average flow distance from the aquifer cell to the MOUSE conduit is <sup>1</sup>/<sub>4</sub> of the horizontal and vertical cell length. This is because the MOUSE conduit may be placed anywhere in a MIKE SHE grid cell, and this position is not resolved in detail in the programme. Hence, the exchange is also assumed to take place both in the vertical and horizontal direction and the average leakage coefficient of the aquifer matrix is (DHI, 2005a):

$$L_{aq} = L_{aqH} + L_{aqV} = \frac{K_{xx}}{\left(\frac{\Delta x}{4}\right)} + \frac{K_{zz}}{\left(\frac{\Delta z}{4}\right)}$$
(Eq. 8.2)

and the resulting total leakage coefficient is (DHI, 2005a):

$$\frac{1}{L_c} = \frac{1}{L_{conduit}} + \frac{1}{L_{aq}}$$
 (Eq. 8.3)

The hydraulic radius,  $R_H$ , used in Eq. 8.1 is taken as either the inner or the outer hydraulic radius of the conduit, depending on whether the flow is from the conduit to the aquifer or vice versa (DHI, 2005a). Thus, the exchange surface is accurately calculated in MOUSE using the cross-sectional data.

Obviously, it is of utmost importance for our modelling purposes that the coupling is described adequately, so that a realistic exchange of water is obtained between matrix and conduit.

By using the leakage coefficient which is based on the aquifer's hydraulic conductivity the MOUSE description of the exchange between matrix and conduit fits well with our conceptual understanding of the system. Only using the hydraulic conductivity of the matrix as the determining parameter for the exchange can be obtained by setting the leakage coefficient of the conduit very high, so that the right-hand side of Eq. 8.3 is dominated by  $L_{aq}$ .

In conclusion, the mathematical description of the conduit-matrix exchange in MIKE SHE/MOUSE seems well suited for a conduit-matrix model of a karst aquifer.

It should however be kept in mind that the modelling of the karstic conduit-matrix system may be inhibited by our understanding of storage in such a system. There are at present three main conceptual understandings of storage in karstic aquifers, according to Bakalowicz (2005). We here use the

conceptual understanding that groundwater is stored in the matrix and this understanding is well described by the MOUSE/MIKE SHE coupling.

The two other possible current conceptual understandings of storage in karst systems are the "Annex-to-Drain" where conduit and matrix flow is decoupled from one another and storage instead takes place in karstic voids developed around conduits (Mangin, 1994 and Marsaud, 1996, both cited in Bakalowicz, 2005); as well as the conceptual understanding of no storage in the aquifer, with buffering only taking place in the unsaturated zone (Lastennet *et al.*, 1995, cited in Bakalowicz, 2005). The "Annex-to-Drain" conceptual understanding may not be simulated by our model but this is not a problem since we have chosen a model which can describe the conceptual choice that we have made.

# 8.3 Conceptual Background for the Simple Conduit-Matrix Model

In order to set up a simple conduit-matrix model it is necessary to have data from the real conduit systems to adjust the model with and calibrate the results to. In general, such data are scarce for all known conduit systems in the model area. The most well-investigated conduit system with regard to cave parameters useful in a hydrological modelling perspective is the Nohoch Nah Chich cave system located about 10 km north of Tulum (see Figure 2.21 in Chapter 2). Cave maps and dimensions of this system have been drawn and measured by Mike Madden, Chuck Stevens and Eric Hutcheson (Cedam Cave Diving Team Survey) (cited in Beddows 2003, 2004 and Smart *et al.*, 2006), and flow velocities have been estimated by dye tracing by Beddows (2003) in about 8.5 km length of cave in the system on a stretch that has the most direct groundwater flow path through the system according to the divers who explored the system (Beddows, 2003). These data have formed the basis for the simple conduit-matrix model which will be presented in the following.

Below, a simple schematic drawing of the conceptual model setup is provided (not to scale).



Zero flux boundary

**Figure 8.1**. Schematic drawing of the simple conduit-matrix model seen from above (not to scale). Arrows indicate flow direction in the conduit due to head difference. Flow direction in the matrix will be seen from simulation results.

The conceptual understanding behind the simple conduit-matrix model is as follows:

- The system is comprised of 1 conduit and the matrix. The unsaturated zone is neglected, and is thus assumed not to have an impact on the groundwater flow in the system. This is acceptable since the system modelled is steady-state, and the unsaturated zone is highly permeable and thus has limited retention capacity.
- The conduit implemented in the model is a simplified representation of the main trunk passage of the Nohoch Nah Chich system. Therefore, the defined conduit catchment stretches lengthwise from the Holbox fracture zone to the coast with the conduit connecting these two boundaries. Although in reality, the length of the mapped Nohoch Nah Chich cave system stretches from the coast to about 6 km inland (straight-line distance), we have conceptually chosen to view the system as connecting the Holbox lineament zone with the coast, i.e. to be about 10 km long. This conceptual understanding is supported by Smart *et al.* (2006) who also mention connecting conduits stretching from the coast, which capture water from the Holbox fracture zone. All these connectors have broadly comparable dimensions, according to Smart *et al.* (2006). It should be kept in mind, however, that in reality this connection may not be a large cave passage all along, but may in the upper part of the system consist of smaller tributaries feeding into a trunk passage further downstream. The smaller tributaries may not even be enterable for human beings.
- In the simple conduit-matrix model bends and changes in slope of the conduit have been neglected and cross-sections have been simplified to be the same throughout the conduit length.
- The catchment is delimited in the width by the expected distance between the conduit and adjacent conduits, i.e. the inter-conduit spacing. However this distance is not known, and therefore various options will be tested. The zero-flux boundaries that define the width of the catchment correspond to dividing streamlines.
- The Holbox fracture zone is expected to be water-bearing, and thus have a certain hydraulic head. Since the Holbox fracture zone constitutes the upstream boundary of the model area, this boundary is therefore perceived as having a constant hydraulic head. Different magnitudes of the upstream head will be tested.
- The downstream boundary is the sea level at the coast, which is taken as a constant head of 0 m.
- Typical flow magnitudes and cross-sectional areas are taken from the data presented in Beddows (2003 and 2004) and the models are adjusted according to these data.
# 8.4 Overall Setup of the Simple Conduit-Matrix Model

Below, the setup and parameters used in the conduit-matrix model are described. These are divided into the setup of the MOUSE model, the setup of the MIKE SHE model and the setup of the coupling between the two.

### 8.4.1 MOUSE Model Setup

The MOUSE setup is defined as two nodes connected by one link – the conduit. The nodes are chosen to be the so-called "outlet" nodes, so they do not have any dimensions. The outlet nodes are per default sealed so water is only allowed to enter through the conduit wall. The term "outlet" does not mean that water seeps out through both nodes; this depends merely on the local water head. The head in the outlet nodes is fixed – downstream it is 0 m, i.e. sea level, and upstream it is set equal to the upstream head of the matrix compartment of the model.

The conduit link was defined with zero slope. The conduit link has a circular cross-section which is set to be constant throughout the length of the conduit. This is chosen because this configuration is suitable for this type of simple modelling. However, it should be kept in mind that this choice is far from being realistic. As described in Chapter 2 and in Smart *et al.* (2006) conduits in the model area are often elliptical and/or fissure passages, i.e. displaying a non-unity ratio of width to height dimensions. According to the literature, some cross-sections in the Nohoch Nah Chich system are also shaped by undercuts and/or repose. In addition, conduits may be filled with speleothems and/or sediment (Smart *et al.*, 2006).

The dimensions of the conduit as well as the friction component will be described under the simulation descriptions below. For the description of friction, it is chosen to use the Manning formula. MOUSE also allows for use of the Chezy formula or the Colebrook & White formulation. Using the Colebrook & White formula is applicable for circular pipes in both the turbulent and the laminar flow regime. By using the Manning formula it is assumed that the flow in the conduits is always turbulent. However, this is acceptable for our purpose, since Beddows (2003) during dye tracing field studies in the Nohoch Nah Chich system found the flow regime to be turbulent.

The default value (slot width: 0.01 m) is used for the width of the Preissman slot, which is a fictitious slot that the calculation scheme inserts when modelling pressurized flow with the Saint Venant equations.

The MOUSE conduit is placed in the centre of the MIKE SHE model domain while ensuring that the conduit from a cross-sectional view is located within one grid cell and not shared by several grid cells in the cross-sectional plane.

It is found that the best suited time steps for the MOUSE model are constant time steps of 5 seconds, since an increase in the length of MOUSE time steps and/or making the time steps adaptive causes the continuity balance in MOUSE to deteriorate in the simulations, in most cases to unacceptable high levels (> 1% in discrepancy of total outflow from the MOUSE component).

#### 8.4.2 <u>MIKE SHE Model Setup</u>

The MIKE SHE model domain is rectangular as depicted in Figure 8.1. The length of the model domain in the flow direction is 10 km, representing the distance from the Holbox fracture zone to the coast. The width of the model domain is in general 200 m unless otherwise stated in the simulations presented below.

The horizontal discretization in the MIKE SHE model is 20 m x 20 m. This is the smallest cell size possible when we have the model domain dimensions mentioned above, since the general max. number of cells in one direction is 500 in MIKE SHE. The model *can* be made with more cells by contacting the software company, but this is not needed for these simulations, since it would increase simulation times and the greater level of detail is not required for our purposes. The vertical discretization of the developed model is only 1 layer.

Model boundaries were described in Section 8.3 and on Figure 8.1.

The topographical surface is set to a uniform level of 20 m above sea level. This is merely done to avoid formation of overland water. Topography is otherwise not relevant for this simulation since the unsaturated zone is not included.

Recharge to the model is generally set to 2 mm/day if not otherwise stated. This recharge is equivalent to about 60% of the average annual precipitation for the area, assuming that it is about 1200 mm/year as mentioned in Villasuso & Ramos (2000) and presented in Chapter 2. The 60% estimate of recharge stems from Beddows (2004), who by hydrological modelling found that recharge must be higher than the generally assumed recharge in the area of 15% (e.g. Hanshaw & Back, 1980), and at least 30% of mean annual precipitation (Beddows, 2004). Beddows (2004) used 30% and 60% of the mean annual precipitation for recharge for her modelling to fit field data.

The hydraulic conductivity of the model is set to be the same both in the horizontal and vertical direction. Although there may be a horizontal anisotropy in the hydraulic conductivity, due to possible increased karstic dissolution in the direction of the regional hydraulic gradient (generally sloping towards the coast), the MIKE SHE software does not allow such a resolution of anisotropy. This is not important for this simple schematic model setup, but may have a non-negligible effect on the results of the regional model. However, the difficulty in obtaining data for the degree of anisotropy in the model area suggests that for now, not taking anisotropy into account can be justified until further data are obtained. The hydraulic conductivity has, unless otherwise stated, been set to 0.001 m/s, based on the *K*-values found in the literature for the Yucatan Peninsula as seen in Figure 2.18 in Chapter 2. A low range value was selected, since the matrix hydraulic conductivity in this model only represents the matrix and smaller fractures, while the higher permeability zone is explicitly accounted for by the inserted conduit.

Specific yield is set to 0.2 (dim. less). This parameter is only relevant for transient models. The simple conduit-matrix model is run as a steady-state model, but because the model failed to converge when using the steady-state solver the steady-state solution was instead produced using a transient solver with constant input (recharge and upstream head), and running it till the solution was stable. Thus, the specific yield parameter had an impact on how quickly steady-state was obtained.

The specific storage coefficient is not used in the model but must be input, and the value  $0.2 \text{ m}^{-1}$  is specified.

The matrix calculations are modelled with a finite difference method and the transient Preconditioned Conjugate Gradient (PCG) solver is used, with no under-relaxation (see Appendix P, Hill (1990) and DHI (2005c) for further descriptions of the method).

The lower level of the model is set as uniform over the whole model area, generally 30 m below sea level unless otherwise mentioned. The effect of instead using a sloping lower level, similar to the expected slope of the halocline, will be tested below.

In order to obtain a faster stabilization to steady-state conditions the initial head was specified as a slope connecting the defined fixed upstream and downstream heads by using fitted analytical model presented in Chapter 5. The time step length used for the MIKE SHE part of the model is 0.1 hrs for both the overland and saturated zone compartment.

### 8.4.3 Coupling Setup

The coupling between the two models is specified in each of the two separate models and in two associated ASCII files used by the models. The coupling is defined as depending both on the leakage coefficient of the aquifer and the matrix (Eq. 8.2 and Eq. 8.3). However, the  $L_{conduit}$  is specified high enough so that only the matrix properties are controlling the exchange between matrix and conduit.

Coupling of MOUSE with overland flow in MIKE SHE is not included since this model will not create overland water.

MIKE SHE inflow to MOUSE is made "smooth" by activating an option in the \*.PFS ASCII file used in the coupling. This is done to ensure a more smooth calculation of exchange flows when MOUSE time steps are small compared to the MIKE SHE time steps (DHI, 2005a) as is the case here. However, no limitations on the inflow or outflow to/from MOUSE are made.

# 8.5 Establishing Conveyance for the Model Conduit

The ability of the conduit to convey water depends in part on the conduit dimensions and in part on the friction factor of the conduit. Both of these parameters are essentially unknown or little known for the conduit systems, since they have a high degree of variation in space. Instead, we may use a lumped parameter – the conveyance – to describe the combined effect of changes in conduit dimensions and roughness. The conveyance of water at a specified hydraulic gradient can, when using the Manning formula (Appendix D, Eq. D.6), be described as:

$$Conveyance = A \cdot R_{H}^{2/3} \cdot M \tag{Eq. 8.4}$$

where *A* is the cross-sectional area of the conduit  $[L^2]$ ,  $R_H$  is the hydraulic radius of the conduit  $[L^{2/3}]$  and *M* is the Manning roughness coefficient  $[L^{1/3} / s]$ . Thus, the conveyance has units of  $[m^3/s]$ . The flow in a conduit thus equals the conveyance multiplied with the square root of the hydraulic gradient (cp. Manning's formula, Appendix D, Eq. D.6).

For the model conduit, a conduit conveyance as close to the conveyance of the cave conduits measured by Beddows (2003) is wanted. This means selecting both appropriate dimensions and an appropriate roughness coefficient. A circular cross-section will be used, to keep the model simple.

The selection of conduit dimensions to be used in the conduit models has been based on the conduit dimensions presented in Beddows (2003), and which are shown in Table 8.1. Note that all the listed conduit segments are in continuation of each other except Site 2 - 3B, which is a branch off the main investigated flow line. The names of the segments refer to the schematic figure of the system which may be seen in Figure 8.2.



Figure 8.2. Schematic figure of the Nohoch Nah Chich system, as depicted by Beddows (2003). Length of segments in kilometres are written along each segment.

conduit segments refer to the schematic drawing of the system seen in Figure 8.2 Indicates no published data.							
Conduit segment	Conduit	Straight-	Cross-	Wetted	Hydraulic	Freshwater	Freshwater
	length *	line	sectional	perimeter	diameter *	velocity	discharge
		distance *	area *	*			- Q
	[m]	[m]	[m <sup>2</sup> ]	[m]	[m]	[m/s]	[m <sup>3</sup> /s]
Injection site – 1	900	740	110	68	6.47	0.011	1.2
Site 1 – 2	1980	980	150	97	6.19	0.010	1.5
Site Red Dog – 3A	1130	650	50	40	5.00	0.015-	0.8-1.5
						0.030	
Site 2 – 3A	2130	1230	90	77	4.67	~0.013	1.2
Site 2 – 3B	910	590	210	102	8.24	0.006	1.3
Site 3A – 4	1400	1050	80	-	4.4	-	-
Site 4 – 5	-	1990	-	-	-	-	-

**Table 8.1**. Data on the Nohoch Nah Chich system. From Beddows (2003) and Beddows (2004). Names of the conduit segments refer to the schematic drawing of the system seen in Figure 8.2. "-" indicates no published data.

\* Data from analysis by Beddows (2003; 2004) of underwater surveys and cross-sections by Hutcheson (1994; 1992, cited in Beddows, 2004).

The hydraulic diameter is a measure used for non-circular conduits, and is equal to 4 times the hydraulic radius,  $R_{H}$ , which again equals the cross-sectional area divided by the wetted perimeter, i.e.  $R_H = A/p_w$ . For circular pipes, the hydraulic diameter is equal to the normal diameter. The hydraulic diameters of the conduits mentioned in Table 8.1 are much smaller than they would have been had they been completely circular pipes that should yield the observed cross-sectional areas. This is due to the larger wetted perimeter of the cave conduits compared to that of normal circular pipes. If calculating the equivalent circular diameter based on the cross-sectional area, diameters between 8 and 16.4 m are obtained (Appendix K).

Therefore, since we will assume a perfectly circular conduit cross-section, to dimension the model conduit it has been chosen to use the measured cross-sectional areas instead of the hydraulic diameters. The mean of the cross-sectional area in the measured Nohoch Nah Chich conduit segments for which flow magnitude has been quantified, is  $122 \text{ m}^2$ . This cross-sectional area yields a mean circular conduit diameter of ~12.5 m, which is used for the model conduit. Given the large variance in conduit cross-sectional areas, even over short distances, it is not particularly meaningful to use an average cross-sectional area based on few and relatively randomly chosen cross-sections. However, this has been done anyway here, due to no other available methods of better estimating a representative conduit size.

To ensure the conduit being placed below sea level, the floor of the conduit was set to be at 15 m below sea level, so the ceiling is 2.5 m below sea level. This also corresponds well with the median cave floor depth of 14 m, mentioned in Chapter 2.The dimensions are illustrated in Figure 8.3.



**Figure 8.3**. Scematic drawing of the vertical setting of the conduit in the model. Figure is thus a cross-sectional view. Not to scale.

The Manning's *M* roughness coefficient is determined based on the friction factors measured by Beddows and presented in Table 2.1 in Chapter 2. Recalculating these friction factors to the corresponding Manning's *M* by using the average conduit diameter of 12.5 m chosen above, yields values as displayed in Table 8.2. As seen, the calculated Manning's *M* range from 0.2 to 7.3 m<sup>1/3</sup>/s, with the smallest values indicating the highest resistance to flow. However, the most recently determined friction factors from the system yield M = 0.2 to 0.3 m<sup>1/3</sup>/s. Therefore, for the model conduit, Manning's

*M* was specified as 0.3  $m^{1/3}$ /s corresponding to a conduit roughness of the same magnitude as found by Beddows (2004).

**Table 8.2**. Manning's M calculated corresponding to a range of friction factors, as determined by Beddows (2003 and 2004). The values have been calculated based on the selected model conduit diameter of 12.5 m, by using Eq. D.8 presented in Appendix D.

Conduit diameter: 12.5 m		f from Bed	f from Beddows (2004)			
f [-]	1	4	11	108	500	1000
M [m <sup>1/3</sup> /s]	7.3	3.7	2.2	0.7	0.3	0.2

## 8.6 Investigation of Magnitude of Upstream Fixed Head

Before the conduit-matrix model is run the magnitude of the upstream boundary's fixed head is investigated with a pure conduit model. The flows obtained in the conduit with the different upstream heads are compared to the conduit flows measured by Beddows (2003). The corresponding MOUSE models can be found in the DVD-appendix.

The setup of the pure conduit model is as described under the setup of the MOUSE model above and in the previous section about dimensions of the model conduit.

#### 8.6.1 Conduit Flows Resulting from Applying the Measured Hydraulic Gradients

Measured hydraulic gradients in the area may be used to get an idea of the possible magnitude of the upstream constant head. Table 8.3 displays the values found in the literature for the Caribbean Coast of the Yucatan Peninsula. As seen, the values range from about 40 mm/km to 130 mm/km. Marín (1990, cited in Alcocer *et al.*, 1998) found a much lower hydraulic gradient of 7-10 mm/km for an area in the Yucatan State.

Hydraulic gradient	Comment	Location	Reference
130 mm/km	Max. value, November	8 km south of Playa del Carmen	Moore <i>et al</i> . (1992)
57.9 mm/km	Error: ± 3 mm/km	From site 32 km inland along the Coba-Tulum road to the coast. Measured in well.	Beddows (2004)
51.9 mm/km	Over difference in relative distance from site to coast Error: ± 29.7 mm/km	Sistema Ponderosa, about 30 km north of Tulum. Measured between cenotes.	Beddows (2004)
37.8 mm/km	Over minimum conduit path between sites Error: ± 21.7 mm/km	Sistema Ponderosa, about 30 km north of Tulum. Measured between cenotes.	Beddows (2004)
92.5 mm/km	Over difference in relative distance from site to coast Error: ± 14.7 mm/km	Sistema Naranjal, roughly 5 km south of Tulum. Measured between cenotes.	Beddows (2004)
57.4 mm/km	Over minimum conduit path between sites Error: ± 9.25 mm/km	Sistema Naranjal, roughly 5 km south of Tulum. Measured between cenotes.	Beddows (2004)

 Table 8.3. Hydraulic gradients measured on the Caribbean Coast of the Yucatan Peninsula.

As seen, the many of the measured values generally have a high error due to the measurement error being proportionally very large compared to the small measured head difference.

Three hydraulic gradients have been chosen spanning the range of the measurements by Beddows (2004), i.e. 90 mm/km, 60 mm/km and 40 mm/km. The gradients have been recalculated to the upstream head they would yield in the model setup which is 10 km long. Thus, upstream constant heads of 900 mm, 600 mm and 400 mm are inserted in the conduit model.

With the above-mentioned conduit dimensions and roughness, these values yield conduit discharges of  $0.75 \text{ m}^3/\text{s}$ ,  $0.61 \text{ m}^3/\text{s}$  and  $0.50 \text{ m}^3/\text{s}$ , respectively.

These values are in the lower range compared to the conduit discharges measured by Beddows (2003) (see Table 8.1). Only the upstream head of 900 mm yields a discharge similar to the smallest discharge measured by Beddows (2003), namely  $0.8 \text{ m}^3$ /s.

#### 8.6.2 <u>Upstream Head Resulting from Applying the Measured Flow in the Conduits</u>

If the discharge in the conduits should be similar to the larger values measured by Beddows (2004) (Table 8.1), it is found that an upstream constant head of 2000 mm yields a discharge of  $1.125 \text{ m}^3$ /s. This corresponds to a water velocity of 0.009 m/s. These values are in the same range as those reported by Beddows (2003). However, the upstream head of 2 m is larger than that expected from the hydraulic gradient measurements available and shown in Table 8.3.

The maximum measured discharge of  $1.5 \text{ m}^3$ /s cannot be obtained with realistic upstream heads. For instance as high a value as 2500 mm at the upstream head boundary results in merely  $1.25 \text{ m}^3$ /s as conduit discharge.

This approach assumes that all water discharging to the sea comes from beyond the Holbox fracture zone, since it does not take into account recharge between the Holbox fracture and the sea. This is of course not true, and recharge will be taken into account in the models presented in the following. However, the large impact of the regional hydraulic gradient on the conduit discharge, when conduit conveyance is kept fixed, is evident from the above experiments.

## 8.7 Baseline Conduit-Matrix Model

A baseline conduit-matrix model has been set up, and used for comparing results from the sensitivity analysis with. The setup is as described in the setup section above.

The model parameters of the Baseline model are summarized in Table 8.4.

Table 8.4. Model parameters of the Baseline conduit-matrix model.	. The model names refer to the name und	er
which the results can be found in the DVD-appendix.		

Model parameter	Value for the Baseline conduit-matrix model				
	(Name: SHEMOUSE W)				
Upstream head	900 mm				
K	0.001 m/s				
Average conduit spacing	200 m				
Conduit conveyance	78.9 m <sup>3</sup> /s (diameter: 12.5 m, $M = 0.3 \text{ m}^{1/3}$ /s)				
Recharge	2 mm (~60% of mean annual precipitation)				
Lower level	- 30 m				

The upstream boundary is in the Baseline model set to a constant head of 900 mm. This value is chosen since, as seen in Section 8.6, it is the only value which fits with both one of the hydraulic gradients measured by Beddows (2004) and the discharge order of magnitude measured by Beddows (2004), although this resulting discharge is in the lower end of what has been measured.

The average conduit spacing of 200 m for the Baseline case is an informed guess based on visual inspection of the Nohoch Nah Chich line maps as shown in Beddows (2004). The effect of changing the average conduit spacing, or model domain width, will be analyzed further below.

The conveyance of the conduit in the Baseline case has been calculated, using Eq. 8.4 and the dimensions and Manning's M chosen above, to be 78.9 m<sup>3</sup>/s.

A very high recharge rate is chosen for the Baseline study. As will be seen later it has relatively little influence on the model to choose a lower recharge. This is because the entire basin is not modelled, but the main contribution of water from the areas upstream of the model domain, are specified through the fixed upstream head. Also, the recharge over the model domain has relatively little impact on the total conduit discharge compared to a model with no recharge at all. In a model with no recharge, discharge is  $0.75 \text{ m}^3/\text{s}$  throughout the conduit, just like was the case in the pure conduit model with the same hydraulic gradient. The Baseline model has a conduit discharge of  $0.73 \text{ m}^3/\text{s}$  upstream, increasing to  $0.77 \text{ m}^3/\text{s}$  downstream. Including recharge thus only increases the conduit discharge by  $0.02 \text{ m}^3/\text{s}$ . Nevertheless, including recharge has a significant influence on the inflow of water from matrix to

conduit, since head differences are increased. When no recharge is present, the matrix only provides  $3.68 \cdot 10^{-5}$  m<sup>3</sup>/s of water over the whole 10 km of conduit length, or about 0.02% of the total outflow of water from the conduit. When including the recharge of 2 mm/day the inflow from the matrix to the conduit constitutes 0.04 m<sup>3</sup>/s or about 5% of the total outflow volume from the conduit. The conduit-matrix model with no recharge can be seen in the DVD-appendix (Name: SHEMOUSE\_V).

In the Baseline conduit-matrix model a uniform lower level of -30 m is applied. The depth of this level will be varied in the sensitivity analysis of the model. In addition, a model has been made which instead uses a sloping lower level similar to the slope of the halocline. This is done in order to investigate whether it is acceptable to use the simplistic uniform lower level of the matrix rather than more realistic conditions. The details of this investigation are shown in Appendix L. It has been found that using a uniform lower level of the aquifer does not have a significant influence on the exchange flow between matrix and conduit, nor on the discharge in the conduit. However, it does impact the matrix discharge, which will be higher than in the case with a sloping halocline to define the lower level of the freshwater lens, and it impacts the outflow ratio between the conduit and the matrix, which will be lower than if a sloping lower level is used. However, using a uniform lower level is found to be acceptable for our simple generic conduit-matrix modelling purposes.

The water balance error of the MIKE SHE component of the Baseline model is 0.37% of the total outflow over the matrix model boundaries, whereas the water balance error of the MOUSE component of the Baseline model is 0.01% of the total outflow from the conduit. Both of these water balance errors are satisfactorily small in order for the models to be used.

The results of the Baseline model are presented below in Figure 8.4, 8.5, 8.6 and in Table 8.5.

The asymmetry which will be seen in the results are caused by an apparent bug in the programme with regard to boundary conditions, as well as by the conduit being placed 10 m from the midpoint of the model domain to ensure that the conduit is not on the boundary between two cells but completely enclosed by one.

The groundwater head pattern calculated by the model at steady state is seen in Figure 8.4. It is seen that generally the head pattern is merely sloping from the specified upstream head to the specified downstream head. The presence of the conduit causes a small drawdown in groundwater head over the conduit. This is seen by the example cross-section displayed in Figure 8.5. The presence of the conduit causes the groundwater flow to be directed towards the conduit and the drawdown caused by this. This is indicated with flow arrows on Figure 8.6. At a distance far from the conduit, the groundwater flow direction is not impacted by the conduit but follows the regional gradient. The conduit thus has a certain catchment zone.

The drawdown of the groundwater head caused by the presence of the conduits, is, as seen in Figure 8.5, very small – only 3.0 mm on one side and 1.8 mm on the other side of the conduit at a midpoint between the upstream and downstream boundaries. Drawdowns of the same magnitude are found over the whole of the model area. The groundwater head drawdowns caused by the conduit are thus negligible in the Baseline case.





**Figure 8.4**. Head pattern of the Baseline model at steady state. Boundary cells have been removed on this figure, since they have misleading values. Axis unit and legend unit is meters above sea level. The figure is a view from above, like Figure 8.1, and is not to scale.



**Figure 8.6**. A close-up in of matrix flow vectors on a section of the matrix model domain. Although only displaying a part of the model domain, the figure is representative for the pattern observed over the whole length of the model area. Axis units are in meters.

Parameter		Baseline Model
	To matrix	0.00036 m <sup>3</sup> /s
Water inflow from unstream end	To conduit	0.73 m³/s
water innow from upstream end	Total inflow	0.73036 m <sup>3</sup> /s
	(sum of the two above)	
Outflow from matrix		0.00067 m <sup>3</sup> /s
Discharge in conduit	Upstream	0.73 m³/s
	At midpoint between	0.75 m <sup>3</sup> /s
	upstream and downstream	
	Downstream	0.77 m <sup>3</sup> /s
Outflow ratio at downstream end		1157
[flow from conduit / flow from matrix]		
Exchange from matrix to conduit,		0.04 m³/s
over the whole length of the conduit		(3163 m <sup>3</sup> /day)
Pressure in conduit	Upstream	900 mm
	At midpoint between	465 mm
	upstream and downstream	
	Downstream	0 mm

**Table 8.5**. Summary of results of the Baseline model. Pressure is indicated in the unit: mm water-coloumn pressure above sea level.

When looking at the results presented in Table 8.5 for the Baseline case, the difference in inflow and outflow of the matrix compared to that of the conduit is clearly noticeable. Although the matrix occupies  $(0.3 * 4800 \text{ m}^2 / 123 \text{ m}^2 =) \sim 12$  times as much cross-sectional void area than the conduit, when assuming a matrix porosity of 0.3<sup>-11</sup>, the conduit inflow and outflow is roughly 2000 and 1200 times larger than that of the matrix, respectively.

This means that flow velocities are much larger in the conduit than in the matrix, as is also expected. This is evident from the following calculations:

Outflow Darcy velocity (q) of Baseline case:

$$q = \frac{Q}{A} = \frac{0.00067m^3/s}{4800m} = 1.4 \cdot 10^{-7} m/s = 0.012m/day$$

This is a rather low Darcy velocity compared to other normal aquifers, which may e.g. have a Darcy velocity of 0.25 m/day. The reason is the very low hydraulic gradient present in the model area.

Pore water velocity  $(v_p)$  of Baseline case, assuming porosity  $(\varphi)$  of 0.3:

$$v_p = \frac{q}{\varphi} = \frac{1.4 \cdot 10^{-7} \, m \, / \, s}{0.3} = 4.6 \cdot 10^{-7} \, m \, / \, s = 0.04 \, m \, / \, day$$

<sup>&</sup>lt;sup>11</sup> Porosity of 0.3 assumed as done in the pre-thesis project based on data from Sonnenborg *et al.* (2001), González-Herrera (1984, cited in Steinich & Marín, 1997) and Villasuso & Ramos (2000).

Matrix cross-sectional area is comprised of 8 cells with dimensions 20 m x 30 m, + in the upstream end an additional 0.9 m in height. However the latter is neglected for these calculations. Thus, matrix cross-sectional area is  $4800 \text{ m}^2$ .

It should be noted that these matrix water velocities are expected to be in the lower range of what would actually occur in the matrix, since the matrix in reality also consists of many small tubes and fractures (secondary porosity features) which is not taken into account here, but would increase matrix water velocities.

Conduit velocity:

$$v_{conduit} = \frac{Q_{conduit}}{A_{conduit}} = \frac{0.77m^3/s}{123m^2} = 0.006m/s = 541m/day$$

This means that water is transported almost 14,000 times faster through the conduit than through the matrix in this simple Baseline conduit-matrix model setup. In actual numbers, it means that it would take 69 years for water in the matrix to be transported 1 km downstream, whereas it would take only 1.6 days for water to move the same distance via the conduit.

It should be noted that the conduit measurements made by Beddows (2003) indicate that water can move even faster through the conduits than shown above (see velocities listed in Table 8.1).

The calculated Darcy velocity of the matrix may also be compared with the exchange velocity of water from the matrix to the conduit. Using the dimensions of the conduit we find the exchange velocity on average to be:

$$v_{exchange} = \frac{Q_{exchange}}{Conduit\_circumference \cdot conduit\_length} = \frac{0.04m^3 / s}{2 \cdot \pi \cdot \frac{12.5m}{2} \cdot 10000m} =$$
$$= 1.01 \cdot 10^{-7} m / s = 0.009m / day$$

Thus, the outflow velocity from the matrix is a factor 1.37 larger than the average exchange velocity. This may be due to a larger head difference at the outflow end compared to the head difference that drives the exchange flow with the conduit.

An example of the water balance output used to calculate the summary of the results of the conduitmatrix model is seen in Appendix M for the Baseline model. For the other conduit-matrix models they can be found in the respective model folder on the DVD-appendix.

### 8.8 Conduit-Matrix Model Sensitivity

Many of the input parameters to the conduit-matrix model will generally be unknown, or only known to a certain degree (e.g. a range of likely values can be known). Therefore, it is important to investigate the sensitivity of the model towards changes in these parameters.

It has been chosen to vary the following parameters:

- Constant groundwater head of the upstream boundary
- Hydraulic conductivity, K
- Average conduit spacing, i.e. width of the model domain
- Conduit conveyance
- Recharge
- Depth of the uniform lower level

Besides these parameters, one could also have chosen to vary other parameters such as: The length of the conduit (since this would influence the volume of water which would enter the conduit from the matrix, due to changed exchange surface area), the number of bends in the conduit in the x-y and the y-z plane (since these are known to characterize real conduit systems), orientation of the conduit water flow direction in relation to the direction of regional groundwater flow (since, as mentioned in Martin & Screaton (2001) this is known to influence the exchange flow between matrix and conduit). However, these latter parameters have not been varied here, since we have chosen to make a rather simple setup. The impact of such factors may instead for instance be investigated with a more complex and realistic conduit-matrix model of e.g. the Nohoch Nah Chich system or the Ox Bel Ha system.

For the sensitivity analysis, prediction scaled sensitivities, as described by Hill (1998) will be used, since they allow comparison of the relative importance of various parameters. Thus, the prediction scaled sensitivity ( $pss_i$ ) [dim. less] is equal to:

$$pss_{j} = \frac{\left(\frac{\Delta z'_{1}}{z'_{1}}\right)}{\left(\frac{\Delta b_{j}}{b_{j}}\right)}$$
(Eq. 8.5)

where  $z'_{l}$  is the simulated prediction (e.g. conduit discharge), and  $b_{j}$  is the j'th estimated parameter (e.g. head at upstream boundary).

Table 8.6 displays the parameters changed for the sensitivity analysis. The conduit conveyance change was implemented by changing the conduit diameter rather than the Manning number. Details and arguments for the chosen variations in the parameters can be found in Appendix N.

Tuble 0.0. I drameters changed in the sensitivity analysis of the simple generic conduct matrix model.						
Model parameter	Value for the Baseline conduit-matrix model	Value for the Model (change in % of	Increase Baseline value)	Value for the Model (change in % of	<b>Decrease</b> Baseline value)	
Upstream head	900 mm	2500 mm (value yielding measured by Bed	(+ 178 %) max. discharge Idows (2003))	400 mm (value yielding r measured by Bed	(- 55 %) nin. hydraulic head dows (2003))	
К	0.001 m/s	0.002 m/s (factor 2 increase	(+ 100 %) e)	0.0005 m/s (factor 2 decreas	(- 50 %) e)	
Average conduit spacing	200 m	1000 m (+400 %)	400 m (+100 %) (factor 2 increase)	100 m (factor 2 decreas	(- 50 %) e)	
Conduit conveyance	78.9 m³/s	157.8 m <sup>3</sup> /s (factor 2 increase	(+ 100 %) e)	39.5 m <sup>3</sup> /s (factor 2 decreas	(- 50 %) e)	
Recharge	2 mm	(nc	one)	1 mm (-50 %) (~30 % of average precipitation)	0.5 mm (-75%) (~15 % of average precipitation)	
l ower level	- 30 m	-40 m	(+ 33 %)	-20 m	(-33 %)	

Table 8.6. Parameters cha	nged in the sensitivi	ty analysis of the sim	nple generic condu	it-matrix model.
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All water balances of the models developed for the sensitivity analysis are acceptable, since error is below 0.1% of outflow from matrix and conduit. This can be verified by looking at the total water balances for each SHE compartment of the model (provided in spreadsheet files in the DVD-appendix under the folder for each model) and by looking at the MOUSE continuity balances (also provided in the DVD-appendix under each model, in the files entitled SUMMARY HD MOUSE2.HTM).

Detailed comments on the sensitivity of the model to each parameter may be found in Appendix N. There, also the absolute values of the results of each model may be found. These may be of interest since the parameters have been varied between realistic values. However, in the following only the results of the calculated prediction scaled sensitivities will be presented and discussed.

It should be mentioned that head patterns are in general always similar to that of the Baseline model, and is therefore generally not presented in the Appendix N. Likewise, the flow directions in the matrix are as presented under the Baseline Model.

Drawdowns of the same magnitude (less than 1 %) as seen in the Baseline case are found in all the models made for the sensitivity analysis, except in two cases, where drawdowns are 11-14 mm and 85-90 mm (see Appendix N, under *Variation in Inter-Conduit Spacing*). Thus, the groundwater head drawdowns caused by the conduit are generally negligible also in the models used in the sensitivity analysis.

#### 8.8.1 Summary of Sensitivity Analysis Results

The results of the sensitivity analysis made on the simple generic conduit-matrix model are summarized in Table 8.7, which shows the prediction scaled sensitivities (pss-values) found by the analysis. In the table, colour coding highlights values numerically larger than 0.50 in orange colour to show parameters that have a very large impact on the predictions. Values numerically between 0.05 and 0.5 are highlighted in yellow to highlight parameters that have a significant impact on the predictions. Values numerically lower than this are left unhighlighted.

The table shows that the <u>upstream head</u> is important for all the analyzed types of predictions except the exchange flow rate, since all these pss-values are numerically larger than 0.05. This means that it is important for further conduit-matrix modelling in the area to measure head differences in the modelled system, as well as to determine if it is conceptually correct that the Holbox lineament zone is an upper boundary which contributes with water and therefore has a certain head. Likewise it is also important to determine if this head is fixed or fluctuates with e.g. time of the year, and what the magnitude of such fluctuations would be.

Table 8.7 shows that the <u>inter-conduit spacing</u> is important for the degree of exchange between matrix and conduit. This is in particular important for the analysis of transport of pollution through the aquifer, since contaminants are transported much faster through the conduits, and therefore have a much lower possibility of being retained or degraded. When transported in conduits contaminants will flow right through to the coast or possibly also Sian Ka'an if a conduit connection between conduit systems in the Tulum/Ox Bel Ha area and the Biosphere Reserve will be found. In addition, determining inter-conduit spacing is important in order to delineate the catchment zone of a conduit. If there are sources of pollution within the catchment zone of a conduit, the conduits will concentrate the flow of this contamination and transport it faster than it would be in the matrix. The location of conduits is also important in relation to water supply in the area, especially if the part of the conduits, which is upstream of a water supply zone, has a catchment zone which is being polluted. Thus, there is a need for further efforts to determine the locations and extents of the conduit systems.

As can also be seen in the table, the <u>conduit conveyance</u> is an important parameter for the magnitude of the conduit discharge, whether it is the conduit diameter or the roughness factor which is changed. Furthermore, an increase in conduit conveyance via a change in the conduit diameter gives an increased infiltration from the matrix because of a larger exchange surface area, but the change in conduit discharge is primarily caused by a change in inflow from the upstream boundary with the specified constant head. As also found by Martin & Screaton (2001), conduit dimensions, and thus conveyance, has in impact on the volume of conduit-matrix exchange flow. However, conveyance change does not influence the average exchange flow *rate* in our model, according to this sensitivity analysis.

The <u>recharge</u> is important in relation to determining the extent of exchange between matrix and conduit. As mentioned above, this is important in relation to e.g. transportation of contaminants from the matrix to the conduit. This shows that there is a need to quantify evapotranspiration rates in the area better. This need was also found in the analytical modelling of the aquifer (presented in Chapter 4 and 5) where it was found that determining the actual rates of recharge was important in order to determine *K*-values better. In addition, the amount of recharge in the basin upstream of the Holbox fracture zone determines the head at the defined upstream boundary of this model. Also for that reason it is important to quantify the recharge, so that the amount of water entering the model from upstream - which is the main water contribution to this type of model - can be assessed adequately.

		Head Increase Model	Head Decrease Model	<i>K</i> Increase Model	<i>K</i> Decrease Model	Inter- Conduit Spacing Increase Model 1	Inter- Conduit Spacing Increase Model 2	Inter- Conduit Spacing Decrease Model	Conveyance Increase Model	Conveyance Decrease Model	Recharge Decrease Model 1	Recharge Decrease Model 2	Deeper Lower Level Model	Shallower Lower Level Model
-	To matrix	1.58	1.45	1.42	1.44	2.15	-0.31	0.78	0.06	0.17	-0.50	-0.48	1.25	1.17
Water inflow	To conduit	0.39	0.62	0	0	-0.03	-0.03	-0.03	1.03	0.93	-0.03	-0.02	0	0
from upstream end	Total inflow (sum of the two above)	0.39	0.62	0	0	-0.03	-0.03	-0.03	1.03	0.93	-0.03	-0.02	0	0
Outflow from matrix		0.76	0.78	0.78	0.81	3.18	1.94	1.22	-0.03	-0.06	0.27	0.26	0.76	0.81
Discharge in conduit	Downstream	0.36	0.58	0	0	0.03	0.03	0.03	0.97	0.99	0.03	0.03	0	0
Outflow ratio at downstream end [flow from conduit / flow from matrix]		-0.17	-0.33	-0.44	-1.30	-0.23	-0.65	-2.96	1.02	1.03	-0.25	-0.26	-0.63	-1.11
Exchange from matrix to conduit, over the whole length of the conduit		0.00	0.00	0	0	1.17	1.24	1.25	0	0.01	1	1	0	0
Infiltration in % of total inflow to conduit		-0.23	-0.72	0	0	1.0	1.0	1.2	-0.52	-1.60	1.04	1.07	0	0

 Table 8.7. Summary of the results of sensitivity analysis of the simple generic conduit-matrix model. Values shown are the prediction scaled sensitivities (pss-values) [dim. less].

 Colour coding highlights values larger than 0.50 (orange colour) and values lower than 0.50 but larger than 0.05.

To determine the <u>hydraulic conductivity</u> and the <u>lower level of the aquifer</u> accurately is mostly important in this model in relation to determining the volume of the matrix-component of the aquifer and how much water is transported through this. *K* and the lower level do not influence the conduit discharge or the degree of exchange between matrix and conduit, according to the sensitivity analysis.

The modelling shows that this simple generic conduit-matrix model only yields a flow of water from matrix to conduit. This is also believed to in reality be the overall case in our study area. However, in addition, as mentioned by Beddows (2004) water may also in certain conduit sections flow from the conduit into the matrix at places where flow paths are obstructed. This can only be simulated with a much more detailed conduit-matrix model which resolves such local high friction areas. Flow from conduit to matrix might also be the case if there are high transpiration losses in the coastal areas.

# 8.9 Simple Equivalent Porous Medium Models For Comparison

A conduit-matrix model may be the most conceptually correct way to model the studied karstic aquifer. However, in the regional model, the model domain is very large and a conduit-matrix model may then be too computationally intensive to use. Therefore, three simple equivalent porous medium models have been developed in MIKE SHE to compare the effect of using the equivalent porous medium (EPM) modelling approach instead of the conduit-matrix approach. The issue of computational execution times of the presented models will be discussed in the subsequent Section 8.10.

The level of complexity for the description of the conduit-matrix aquifer system gradually decreases for the three EPM models presented in this section. The first model is a 3-layer model where the highpermeable zone has the same cross-sectional area as the conduit in the conduit-matrix model presented earlier. However, a 3-layer EPM model is more computationally intensive to run than a 1-layer EPM model. Therefore, the results of applying a 1-layer EPM model are also investigated, in which the high-permeable zone stretches from the lower level of the model to the topographical surface. The results of these models compared to the Baseline conduit-matrix model will be discussed below. These two model types would then be able to represent larger regional-scale structures, which may be either large regional conductivity value would be for a medium which should represent the entire aquifer block of both matrix and conduit. This is done below with the so-called block-EPM model, the results of which should then be applicable for regional-scale modelling where a higher *K*-value is used for geological areas where conduit density is known to be very high.

#### 8.9.1 <u>Setup and Results of the Equivalent Porous Medium Models</u>

The 3-layer equivalent porous medium model (in the following called: the 3-layer EPM model) is built in exactly the same way as the Baseline conduit-matrix model, except for the MOUSE-conduit. Instead of the conduit, the model is defined with 3 layers, and in the middle layer, a zone of higher permeability is defined at the same location as the conduit was at. This is illustrated in Figure 8.7. The high-permeability zone necessarily has to be 1 cell wide (i.e. 20 m) and rectangular in cross-section. However, the size is adjusted so the high-permeable zone has approximately the same cross-sectional area as the conduit had.

Thus, the depth of the zone of higher permeability is set to 6.25 m, yielding a cross-sectional area of 125 m<sup>2</sup> (conduit cross-sectional area was 123 m<sup>2</sup>). The top of the high-permeability zone is placed 2.5 m below sea level as in the conduit-matrix model. Specific yield and specific storage is set to 1 in the high-permeability zone.



**Figure 8.7**. Schematic drawing of a cross-section of the 3-layer equivalent porous medium model. Dotted area is matrix, white area is high permeability zone. Not to scale.

The 1-layer EPM model has the same model setup as the 3-layer EPM model, except that there is now only one layer in the model and thus the high-permeable zone stretches in depth from the lower level of the model to the topographical surface. This is illustrated in Figure 8.8.



**Figure 8.8**. Schematic drawing of a cross-section of the 1-layer equivalent porous medium model. Dotted area is matrix, white area is high permeability zone. Not to scale.

The models are run as a steady-state model in MIKE SHE. The hydraulic conductivity of the highpermeable zone is calibrated so as to obtain a discharge in the high-permeability zone of the same magnitude as that seen in the Baseline conduit-matrix model. The reason for calibrating the model after the conduit discharge is that this is an important parameter if the model is e.g. to be used for modelling of pollution transport and/or for delineation of groundwater protection zones.

Similar conduit discharges is obtained by using a  $K_{\text{high permeability}} = 67 \text{ m/s}$  in the 3-layer model (yielding discharges between 0.74 and 0.77 m<sup>3</sup>/s) and by using a  $K_{\text{high permeability}} = 13 \text{ m/s}$  in the 1-layer model (yielding discharges between 0.70 and 0.73 m<sup>3</sup>/s) <sup>12</sup>.

In the testing of the model it has also been found that a  $K_{\text{high permeability}} = 100 \text{ m/s}$  in the 3-layer model, and a  $K_{\text{high permeability}} = 20 \text{ m/s}$  in the 1-layer model, yields a discharge in the high-permeable zone of 1.1 m<sup>3</sup>/s, i.e. of the same magnitude as the higher values measured by Beddows (2003) in Nohoch Nah Chich.

The hydraulic heads resulting from the model are very similar to those produced by the Baseline conduitmatrix model and the differences are negligible (less than 6 mm). However, at the upstream and downstream ends of the models, the EPM models are seen to have slightly higher heads (0.5 to 1 mm) than the Baseline conduit-matrix model. The drawdowns in the EPM models are 1.4 to 3.3 mm, and thus in the same range as in the Baseline conduit-matrix model, and also negligible.

Table 8.8 shows a comparison between the output of the 3-layer and 1-layer EPM models and the Baseline conduit-matrix model. It is seen that overall, the discharges of the "conduit" are more or less the same. The infiltration from matrix to conduit is 1% lower in the EPM models, but this is evaluated to be acceptable, since the infiltration values are still in the same range.

The discharges of the high-permeability zone in the 1-layer EPM model are lower, but this is due to the calibration of the model. However, the exchange rate and volume of infiltration is not much different from that in the Baseline conduit-matrix model.

Inflow to and outflow from the matrix is seen to be somewhat smaller in the EMP models than in the Baseline conduit-matrix model. The 25% lower inflow to the 3-layer EPM model may be caused by the higher heads at the upstream end in the model compared to the conduit-matrix model. Thus, outflow also becomes lower, but not to as great an extent (only 12 % lower), probably due to the exchange with the conduit. In the 1-layer model, matrix inflow is almost the same as in the Baseline conduit-matrix model, but outflow is 25% lower. This can be caused by the fact that in this model, precipitation over the high-permeability zone contributes with flow to this high-permeability zone, whereas in the other models, precipitation contributes with water to the matrix only. Thus, in this model, the matrix compartment is "missing" the input of water from the precipitation over the conduit.

<sup>&</sup>lt;sup>12</sup> A  $K_{\text{high permeability}} = 14$  m/s yields discharges of 0.75 to 0.79 m/s, i.e. slightly higher than those seen in the Baseline conduit-matrix model, and could also have been used. Yet, here it has been chosen to present the results from using the  $K_{\text{high permeability}} = 13$  m/s.

		Baseline Conduit- Matrix Model	3-Layer Equiv. Perm. Medium Model, <i>K</i> = 67 m/s	1-Layer Equiv. Perm. Medium Model, <i>K</i> = 13 m/s
		(Name: SHEMOUSE_W)	(Name: SHE_A)	(Name: SHE_B)
	To matrix	0.00036 m <sup>3</sup> /s	0.00027 m <sup>3</sup> /s	0.00034 m <sup>3</sup> /s (*)
Water inflow from	To conduit	0.73 m <sup>3</sup> /s	0.74 m <sup>3</sup> /s	0.70 m <sup>3</sup> /s (*)
upstream end	Total inflow (sum of the two above)	0.73036 m³/s	0.74027 m <sup>3</sup> /s	0.70034 m³/s (*)
Outflow from matrix	•	0.00067 m <sup>3</sup> /s	0.00059 m <sup>3</sup> /s	0.00050 m <sup>3</sup> /s (*)
Discharge in conduit	Upstream	0.73 m <sup>3</sup> /s	0.74 m <sup>3</sup> /s	0.70 m <sup>3</sup> /s (*)
	At midpoint between upstream and downstream	0.75 m³/s	0.76 m³/s	0.71 m³/s (*)
	Downstream	0.77 m <sup>3</sup> /s	0.77 m <sup>3</sup> /s	0.73 m <sup>3</sup> /s (*)
Outflow ratio at downstream end [flow from conduit / flow from matrix]		1157	1305	1448 (*)
Exchange from matrix to conduit, over the whole length of the conduit		0.04 m³/s (3163 m²/day)	0.03 m <sup>3</sup> /s (2592 m <sup>2</sup> /day)	0.03 m³/s (*) (2592 m²/day)
Infiltration in % of total inflow to conduit		~5 %	~4 %	~4 % (*)

(\*) Due to the way the 1-layer EPM model is built, in this table, the values of the "conduit" represents the whole zone of increased permeability, i.e. also the areas above and below where the actual conduit would be which would actually constitute part of the matrix. Thus, the "conduit" values also include a small part of the actual matrix, and the "matrix" part is missing a small part of the actual whole matrix component. However, the differences this causes are evaluated to be negligible. In addition, precipitation over the high-permeable zone contributes directly with water to the "conduit" in this model, and not to the matrix, as in the other models.

The block-EPM model is made like the other models but without a highly permeable zone. The *K*-value of the matrix has been calibrated to obtain the same inflow and outflow to the block as was found for the Baseline Conduit-Matrix model. Thus, it is found that when using K = 0.85 m/s, inflow and outflow to and from the total model domain is 0.71 m<sup>3</sup>/s and 0.78 m<sup>3</sup>/s, respectively; - values which are of the same magnitude as the Baseline conduit-matrix values seen from e.g. Table 8.8. In addition, using a K = 1.5 m/s yields inflow and outflow similar to the higher range values measured by Beddows (2003), namely 1.3 m<sup>3</sup>/s and 1.4 m<sup>3</sup>/s. The block-EPM model has no drawdowns, since the hydraulic conductivity is uniform over the model domain, and the head differences compared to the Baseline conduit-matrix model are on average zero mm, and maximum  $\pm 3$  mm, i.e. negligible. The results of the block-EPM model may be studied further in the DVD-appendix (Name: SHE\_C).

#### 8.9.2 Discussion & Conclusions

The results of the block-EPM model show that areas with known high conduit density, e.g. the geologic area near Tulum, may be replaced by a geologic unit with a higher hydraulic conductivity for a very

simplistic representation. To replace the simple conduit-matrix system constructed here, it has been found that a hydraulic conductivity equal to between K = 0.85 m/s and K = 1.5 m/s could yield similar flows through the aquifer block as those measured in the Nohoch Nah Chich system. These K-values could be starting values in a regional model for such a high-permeable geologic area. Using these values would imply that the same hydraulic gradient as in the simple EPM-model is assumed valid for the regional high-permeable area. This assumption is believed to be valid since the hydraulic gradient used is a measured value from this particular area in question. However, application of the found K-values requires that the conduit-density (or inter-conduit spacing) as well as the conveyance of the conduits in the geologic area are similar to those used here. If, for instance, the inter-conduit spacing is larger than that used in the current block-EPM model, the flow of water through the matrix would be overestimated with the here derived K-value, and vice versa. The inter-conduit spacing used here translates to a conduit density of (10 km conduit / (10 km  $\cdot$  0.2m surface area)) = 5 km/km<sup>2</sup>. Smart *et al.* (2006) states conduit density in the Tulum-area to be 1.8 km/km<sup>2</sup>, while in the Ox Bel Ha/Naranjal/Yax Chen area it is 4.3 km/km<sup>2</sup>, and for the individual Ox Bel Ha system and the Nohoch Nah Chich systems it is 6.5 and 6.8 km/km<sup>2</sup>, respectively. Thus, the conduit density modelled with the simple models here are in the same range as estimates for systems in the area, but it in the higher range compared with the overall conduit density value for the Tulum area. The conveyance of the conduit systems is generally not known, except for the data used here; collected by Beddows (2003).

The experiments with the simple 3-layer and 1-layer EPM models show that it is possible to use the EPM modelling approach instead of the conduit-matrix modelling approach to resolve a conduit and get more or less the same results. These EPM models should then be calibrated using the K of the high-permeability zone to obtain a discharge in this zone of the same magnitude as that measured in a conduit system in the field. The EPM models may differ in relation to inflow and outflow from the matrix, and therefore also with respect to the outflow ratio, and may reduce infiltration volumes slightly. In addition, it is a somewhat more difficult to calculate the exact inflow and outflow from matrix and conduit, respectively, since it is not a direct output of the MIKE SHE water balance. However, the advantage of the EPM models is that they are simpler to build, and can be faster to run.

For the 3-layer and 1-layer EPM model, establishing the hydraulic conductivity of the high-permeability zone may be done by calibrating after a known or wanted magnitude of discharge in this zone. For a 20 m wide structure in a 1-layer model, a starting value could for instance be 13 m/s as seen in the experiments presented above. However, the structures in the regional model will be 1 km wide, i.e. 50 times as wide as the structures modelled here.

What we are actually trying to do by applying an EPM model instead of a conduit-matrix model is to convert the discharge of the conduit system to an equivalent discharge in a high-permeability zone in an EPM model. However, the formulations for this discharge in these two systems are different. According to the Manning formula, in a conduit system discharge is equal to:

$$Q = Conveyance \cdot \sqrt{(dh/dl)}$$
(Eq. 8.6)

In an equivalent porous medium discharge is, according to Darcy's Law, equal to:

$$Q = -K \cdot A \cdot (dh/dl)$$
 (Eq. 8.7)

Under a fixed hydraulic gradient, it is in an EPM model therefore both the cross-sectional area and the K-value which controls the conveyance<sup>13</sup>. Therefore, a K-value, which gives a discharge (and conveyance of water) of the correct order of magnitude in a certain setup, must be scaled according to the cross-sectional area of the model in order to yield a conveyance of the right magnitude. If the K-value is not scaled accordingly, the conveyance of water through the zone will simply become too large or too small.

In the 3-layer model, a  $K_{\text{high permeability}} = 67 \text{ m/s}$  was found. In the 1-layer model, the cross-sectional area of the high-permeable zone is increased by approximately a factor 5 compared to the 3-layer model (3-layer model cross-sectional area: 125 m<sup>2</sup>, 1-layer model cross-sectional area: ca. 30 m  $\cdot$  20 m = 600 m<sup>2</sup>). At the same time it was found that to obtain the same "conduit" discharge as in the 3-layer EPM model (i.e. to obtain the same conveyance under the same hydraulic gradient) the  $K_{\text{high permeability}}$  should also be reduced by approximately a factor 5 to ca. 13 m/s.

Therefore, one could think that for structures in the regional model which are thought to represent regional conduits, a starting value for their *K*-values could be obtained by scaling the *K*-values from the simple EPM models with the cross-sectional area of the regional structure. It is an advantage to be able to use a simple EPM model to obtain a first guess of the *K*-value, because this model is much faster to run and can therefore be adjusted more rapidly. Thus, at a location relatively close to the coast, where the depth of the aquifer could be expected to be e.g. 30 m, the cross-sectional area would be 30,000 m<sup>2</sup>, i.e. a factor 50 larger than the cross-sectional area of the structure in the 1-layer EPM model. Hence, a first value for a  $K_{\text{high permeability}}$  to represent a structure in the regional model could be 13 m/s / 50 = 0.26 m/s. Under the same hydraulic gradient as that of the simple models, the discharge in the high-permeability zone would then be about 0.77 m<sup>3</sup>/s. However, the hydraulic gradient may not necessarily be the same in other areas of the model area, especially if the high-permeability zone is not directed perpendicular to the coast. Therefore, *K*-values of high-permeability zones should always be calibrated further in the actual model using known discharges in the zone. However, in the case of lack of information to calibrate with, a first-order approach could be to use the derived  $K_{\text{high permeability}}$  from an EPM model, scaled according to the cross-sectional area, such as the value of 0.26 m/s.

However, the large regional conduits or structures which will be modelled in the regional model are expected to have a higher discharge than those conduit discharges measured by Beddows (2003). To get a first estimate of discharges in larger conduit systems, information reported by divers in the area can be used. Le Maillot (2006) reported flow velocities of the entrance to the Caapechen system in Sian Ka'an to be similar to the velocity of a diving scooter, i.e. ca. 1 m/s, which is a factor 100 larger than the velocities measured by Beddows (2003). This corresponds well with that divers report a much larger flow in the Caapechen system than in other cave systems they have explored in the area (Le Maillot 2006, Devos, 2006). The Caapechen system could be part of larger structures identified, e.g. the ones near Vigia Chico. Assuming a lower range diameter of the Caapechen outlet of 4 m, the reported flow velocity yields a discharge of 13 m<sup>3</sup>/s. Now assuming that this structure is a regional-scale conduit, which we will model with a 1-layer model, the *K*-value has to be scaled according to the new (larger) cross-sectional area this high-permeable zone will have in the model. The 1-layer EPM model yields  $K_{\text{high permeability}} = \sim 200$  m/s when calibrated according to this conduit discharge (giving a discharge of 11 m<sup>3</sup>/s). Recalculating this value to a 1 km wide structure, 30 m deep, this would yield a  $K_{\text{high permeability}} = 4$ 

<sup>&</sup>lt;sup>13</sup> Note, however, that  $-K \cdot A$  is not *equal* to the conveyance. Rather, the conveyance of a conduit system would be equal to  $-K \cdot A \cdot \sqrt{(dh/dl)}$ , except for the important issue that the two cannot in fact be equated, because the Manning equation describes fully turbulent flow while Darcy's Law describes laminar flow, and thus the equations describe two different flow regimes. However, this fact is purposely ignored when applying an EPM model as a simplification of a conduit-matrix model.

m/s, which could be a reasonable starting value for the hydraulic conductivity of a structure in a regional model. This approach, however, still assumes that the hydraulic gradient is the same as before. The *K*-value of 4 m/s should then also be calibrated further in the regional model. The conduit flow of 13 m<sup>3</sup>/s could be a lower range value, since if the outlet in Caapechen is larger than  $\emptyset = 4$  m, the flow in the system would also be larger, if calculating the measured flow velocity.

# 8.10 Computational Costs of a Conduit-Matrix Model

Table 8.9 displays the computational execution times of the Baseline conduit-matrix model, the steady state 3- and 1-layer EPM models and transient versions of these EPM models. These models are compared because they resolve the conduit explicitly in one way or another. All models were run for 2 months, since this was the maximum time it took for the models to stabilize. Transient models were, as expected, found to yield the same head- and flow results as their steady-state counterparts.

	Computational execution time	Comment
Baseline conduit-matrix model	997 s = 17 min	Model is stable after ~1/2 month
(name: SHEMOUSE_W)		
3-layer EPM model, steady state	4 s	
(name: SHE_A)		
1-layer EPM model, steady state	3 s	
(name: SHE_B)		
3-layer EPM model, transient	1367 s = 23 min	Model is stable after ~2 months
(name: SHE_A_transient)		
1-layer EPM model, transient	370 s = 6 min	Model is stable after ~1/2 month
(name: SHE_B_transient)		

**Table 8.9**. Computational execution times of the simple Baseline conduit-matrix model and the simple equivalent porous media (EPM) models. All models have been run for 2 months.

As seen in Table 8.9, the conduit-matrix model is very computationally costly compared to the *steady state* EPM models, since it takes about 250 times longer to run the conduit-matrix model. However, as was seen in the pre-thesis, it is not possible to run our regional model as a steady-state model, since it crashes. Therefore, it must be run as a transient model with constant input until it gives steady-state results.

Of the transient models, it is seen that it is computationally cheapest to run the 1-layer EPM model, since it is a factor 2.7 faster to run than the Baseline conduit-matrix model. However, surprisingly, the secondfastest model is the Baseline conduit-matrix model rather than the 3-layer EPM model. Thus, if the results from these simple small test models can be assumed to be applicable to larger and more complex models too, it is more computationally efficient in run-time to construct a conduit-matrix model than a 3layer EPM model, when a higher degree of detail is wanted for modelling the real conduit and structure systems. This is nice because the conduit-matrix model is conceptually more correct than an EPM model. On a regional scale, a 1-layer EPM model should however be chosen based on the computational execution time.

Many factors, such as, number of cells in the model grid, number of layers in the model, number of time steps, computer speed and the model parameters and characteristics, influence the computational

execution time of a hydrological model. Thus, also large differences in hydraulic conductivities of adjacent cells may increase model execution time (Hill, 1998). D'Agnese *et al.* (1998, cited in Hill, 1998) found that their hydrological model could be run about 6 times faster by introducing intermediate *K*-values between cells with a factor 5 difference in hydraulic conductivity. An intermediate *K* zone, with K = 0.1 m/s was therefore introduced in the 1-layer EPM model, to see if this would improve the execution time of this model. However, it took 385 s (6.4 min) to run this model, and thus, this modification did not improve computer execution time in our case, and this method will therefore not be attempted in the regional model.

# 8.11 Discussion of Different Modelling Concept Choices for Further Simulations of the Area

The conduit-matrix model type is conceptually more correct than the EPM model. In the EPM model, flow can only be modeled as laminar flow, which is conceptually not correct, at least for many conduit sections. This may have an impact when assessing flow velocities from the model as well as e.g. results from a particle tracking module. Particle tracking is a useful function for examining transport and spreading of contaminants, but in the software used here, the particle tracking module only works in the matrix compartment (MIKE SHE), and thus not cannot be transferred into the conduit compartment (MOUSE) in the coupled model version (DHI, 2005a). Therefore, a conduit-matrix model made with MIKE SHE/MOUSE would unfortunately currently not be able to illustrate the propagation of pollution in a matrix/conduit system. For modeling pollution spread with the examined software, a MIKE SHE model with high permeability zones must therefore be used despite its less correct flow descriptions. Otherwise, the possibility of using other water modeling software systems should be examined, or a particle tracking module should be written which can take into consideration flow between the two compartments.

Another advantage of using the conduit-matrix modelling with MIKE SHE/MOUSE is that it is possible to obtain simulated flow velocities for different conduit sections, which could then be compared to actual field measurements. It is also possible to specify different sections of the conduit for which a different leakage factor and roughness coefficient can be set. This may be useful for calibration of detailed models of conduit sections, if more data from conduit systems are obtained. Furthermore, it is easier to specify accurate cross-sections along the conduits when using the MOUSE software, as well as to specify the variation of the conduit systems in the x-, y- and z-planes.

As a contrast, in MIKE SHE specification of roughness and leakage factors for high permeability zones can be done by setting different  $K_{high permeability}$  for different grid cells but the level of detail depends on the cell size specified, and the values cannot be compared directly with literature values of friction factors. Furthermore, in an EPM model made with MIKE SHE, cross-sections are necessarily square and their minimum size depends on the grid cell size specified.

If using the combined MIKE SHE/MOUSE model type it should be possible to get a better feeling for the friction factors in the karst system, which may then be compared with those in other systems. However, such an understanding requires a good calibration of the model. In particular, the leakage factor and the friction factor have to be well determined, since both parameters influence the discharges and velocities of the conduits. It is hard in practice to measure the leakage factor, and both leakage factor and friction factor may vary significantly over even small distances in space. Alternatively, their values

may be determined by calibration, but given the often limited knowledge on both friction factors and leakage factors, it will probably often be necessary to calibrate these two parameters together as a lumped estimate.

The combination of MIKE SHE/MOUSE seems rather well suited for karst modeling, but it requires that the value of many different parameters are determined or calibrated. A MIKE SHE/MOUSE model type may thus be useful to model limited conduit sections where conduit parameters such as cross-sections, friction factors and flows are known and this method may then increase our understanding of such systems. In addition, it is interesting to notice that, at least for the transient model setups presented here, a MIKE SHE/MOUSE model is computationally less intensive than a 3-layer EPM MIKE SHE model of the same setup, and at the same time has a conceptually more correct description of the flow.

However, due to the generally limited knowledge on the karst conduits and their parameters it is assessed that using the 1-layer EPM model with MIKE SHE would be most suitable for a regional-scale model. It yields less information than a conduit-matrix model but also has fewer parameters to set and is simpler to build and use. Furthermore, it is computationally less intensive than a conduit-matrix model, with about a factor 2.7 difference in computational time for the test setups used here.

# 9 Regional-Scale Hydrological Model

As found in Chapter 8 it is possible to use the equivalent porous medium modelling approach instead of the conduit-matrix modelling approach to resolve a conduit and get more or less the same results, with a degree of detail which is appropriate for a regional-scale model. This is particularly the case for the 1-layer model, which is computationally cheaper than the 3-layer model. A steady state regional-scale equivalent porous medium model was set up in the pre-thesis project for the then defined model area. The model was a strong simplification of the system and a good calibration of the model was not possible due to lack of data.

One of the main purposes of the field trip has therefore been to collect data that can be used to improve the quality of the regional-scale model, such as input data, e.g. local climate data and data on geology and the location of the lower layer of the aquifer (i.e. the halocline), as well as data that can be used for calibration of the model, such as water level measurements.

In the following an improved steady state regional model is developed based on the collected data.

## 9.1 Purpose

When focusing on the most urgent threat to the water resources of the Sian Ka'an Biosphere Reserve, which is believed to be the proposed urban development plan for Tulum, it is perhaps difficult to see the relevance of a regional-scale groundwater model, as the most important processes in this regard takes place in a relatively small geographical area. However, without a regional-scale groundwater model it is very difficult to identify the areas that contribute with water to Sian Ka'an, and how important the surrounding areas are in this respect. A good regional hydrological model is thus a prerequisite for a more detailed analysis of the flow patterns between the Tulum area and Sian Ka'an.

The regional-scale groundwater model has the following purposes:

- To identify the main flow paths in the model area and the main areas that contribute with water to the Sian Ka'an Biosphere Reserve.
- To determine the order of magnitude of the hydraulic conductivity, *K*, for the aquifer and determine travelling times for water to reach the Sian Ka'an Biosphere Reserve.

# 9.2 Conceptual Understanding of the System

The conceptual understanding behind the regional-scale groundwater model is as follows:

The area, which is expected to contribute with water to the Sian Ka'an Biosphere Reserve and which is subject to modelling is in the horizontal plane defined by topography and current knowledge of flow divides as described in Chapter 2. On the basis of the current understanding of the area, the model boundaries are assumed to be fixed in time, despite the fact that in karst areas it is known that catchment boundaries may vary in time, e.g. in response to seasonal changes in precipitation (Ford & Williams, 1989; White, 2003; Bonacci & Živaljevíc, 1993). The boundary conditions are a constant head boundary at the coast and no-flux boundaries inland. The head at the coast boundary is mean sea level, i.e. 0 m.

The model area is conceptualized as consisting of an unconfined aquifer and a connected overland flow compartment, to describe the wetlands and flooded areas known to occur in the model area.

The aquifer is made up by infiltrated rainwater floating on top of underlying saline water intruding from the sea. For the aquifer, only the freshwater lens is included in the model, as this is the water body of interest to our purpose, and the freshwater and saltwater compartments are regarded as immiscible, which is a simplification of the actual conditions. The lower level of the freshwater lens (the halocline) thus defines the lower boundary of the groundwater model. The position of this lower boundary in the vertical direction is regarded to be constant in time, for our modelling purposes, as supported by the findings of Moore *et al.* (1992). Escolero *et al.* (2005) showed the spring-like effect on the halocline that extreme precipitation events can have on the Yucatan aquifer. Such changes are considered to be insignificant for the steady-state regional-scale groundwater model, since the precipitation input is an average yearly quantity. Variation in the depth of the halocline should therefore only be included if a smaller section of the model area is studied in a time-varying perspective and more details will be included on extreme rain events. Thus, the thickness of the aquifer (freshwater lens) in this model will only vary with time due to variable groundwater tables, i.e. in the upward direction and not in the downward direction.

Recharge to the aquifer is assumed to be solely autogenic (i.e. diffuse input of precipitation), since the literature does not tell of any allogenic recharge points in the model area. Recharge will be taken as the incoming precipitation over the model area minus the actual evapotranspiration. The possible groundwater subsurface inflow to Quintana Roo proposed by Lesser (1980, cited in Villasuso & Ramos, 2000) is ignored because the original reference was not available to us so it was not possible for us to evaluate the validity of his estimate. In the literature actual evapotranspiration volumes is indicated to possibly range from 40% (Beddows, 2004) to 85% (Villasuso & Ramos, 2000; Alcocer *et al.*, 1998) of mean annual precipitation. Since the aquifer is solely fed by infiltrated precipitation, and all rainwater that is not evapotranspired is expected to infiltrate, the recharge is consequently in the interval 15% to 60% of mean annual precipitation. It has been chosen to primarily model with a recharge of 30% and show the effect of the highest (60%) possible recharge when relevant.

Discharge from the actual aquifer is known to take place both as diffuse discharge through the matrix and as focused discharge through thousands of large and small submarine springs distributed along the coast, due to their higher hydraulic conductivities. However, these focused points of discharge will not be resolved in the model since they occur on a sub-grid scale.

There is a tidal variation of  $\pm 0.30$  m along the coast of the model area (Moore *et al.* 1993; Beddows, 2004), which could be incorporated in the model with a time-varying boundary condition at the coast to see the effects of the tide on the model, and then compared with the effects reported by Moore *et al.* (1992) and Beddows (2004). As described in Chapter 2 the tidal effect can be separated into a seasonal and a daily component and only the relevant oscillation patterns should be considered in time-varying models, e.g. if it is based on monthly (seasonal) or daily precipitation data. However, the size of the water level fluctuations caused by tide (~ 3-5 cm 10 km inland) is considered too small to be of importance in a regional-scale groundwater model, and should only be included if a small-scale transient study of a near coastal area (such as the Tulum area) is carried out. Therefore, tidal variations have not been taken into consideration in our regional-scale model.

Assuming only a groundwater and an overland flow component means that water storage in the unsaturated zone is disregarded. This means that any storage in this compartment is not included, and storage of water can only take place in the aquifer or as surface water bodies. This approach is chosen based on the reported rapid infiltration rates of the area (e.g. Escolero *et al.*, 2000; Pacheco *et al.*, 2001). The possibility of the unsaturated zone delaying infiltration with ten to hundreds of years as stated by Beddows (2004) is thus disregarded. This is reasonable since the model developed is a steady state model with average annual precipitation as an input.

The eight different geologic formations present in the model area (INEGI, no year) make it possible to have each formation represented by a different value of the hydraulic conductivity. No information has been found in the literature on representative values of *K* for these geological units. However, it is expected that the older geological units in the interior of the peninsula are more cemented than the younger formations, especially than the formations in the coastal zone. This would yield greater frequency of dissolution and collapse in younger limestones compared to in the older, and thus give a reduced permeability of the older limestones compared to the younger (Smart *et al.*, 2006). This situation may be incorporated via varying *K*-values in the different geologic formations. Yet, due to the limited geological knowledge of the area there is no background for a detailed ascription of *K*-values to the various geological units. The hydraulic conductivities in the various geological formations are thus calibration parameters.

The geological units are divided into three hydraulic conductivity classes. It will be assumed that the Quaternary/ejecta geological units have a low hydraulic conductivity due to their reported clay-like characteristics and the fact that they underlie inundated areas (Chapter 2). Medium hydraulic conductivity is assigned to the cemented Palaeocene deposits in the interior part of the Peninsula deposits and high hydraulic conductivity is assigned to the remaining Eocene, Oligocene, Miocene, Pliocene and Pleistocene deposits, which cover the main part of the model area. The model is thus conceptualized as a heterogeneous model domain, and the output of this will be compared with the result of assuming the same hydraulic conductivity all over the model area.

Anisotropy is however disregarded in the present regional-scale hydrological model because no estimates of the degree of anisotropy is currently available and since the software used does not allow for specification of different longitudinal and transvers hydraulic conductivity.

Conduits are conceptualized as high permeability zones as are also areas with a high density of cenotes, faults and fractures and structural features as described and delineated in Chapter 6. These features are all ascribed high hydraulic conductivity, but apart from that they are very different in nature and it is difficult to generalize on the probable order of magnitude of their hydraulic conductivity. The simple

conduit-matrix model and equivalent porous medium model developed in Chapter 6, suggested a K of ~4 m/s in the conduit in the equivalent porous medium model, which is in the same order of magnitude as the conductivity assigned to high-porosity area in the "Ring of Cenotes" in Yucatan state in mathematical model developed by González-Herrera *et al.* (2002).

The large faults and fracture zones described in Chapter 2, i.e. the Holbox fracture zone, the Rio Hondo fault zone and the fault suggested by Perry *et al.* (2002) will be modelled explicitly as high permeability zones, in different model scenarios. The smaller individual fractures indicated on the INEGI map (no year) will not be modelled explicitly since they are not expected to have a significant impact on the regional groundwater flow and since large differences in hydraulic conductivities of adjacent cells may increase model execution time considerably (Hill, 1998).

The vertical extent of the faults and other high permeability features is not known. To increase computational efficiency the features are set to extend all the way through the freshwater lens and thus be present in the entire vertical extent of the computational layer.

The hypothesized inflow to the model area from the Holbox fracture zone (Marín, 2003, cited in ASK, 2003b, and described in Chapter 2) is not included in the current conceptual model.

Beddows (2004) has mentioned elevated water tables in a 1 km belt along the coast in the Tulum area. This can possibly be explained by a low permeability geological zone in this coastal margin, since also cave explorers have reported that conduits in this same area are small and maze-like and may be parallel to the coast (Schmittner, pers. comm., 2006). This has only been reported in the area north of the Sian Ka'an Biosphere Reserve and it is therefore not known if the same conditions are found all along the coast. However, this may be further explored with the model.

The flow in the aquifer matrix is assumed to be laminar, while the flows in the wetlands and the subsurface conduits may be laminar or turbulent. However, the software is limited to only modelling the flow in the high permeability zones as laminar, as a consequence of the equivalent porous medium approach. In addition, the software only allows for describing the overland flow as turbulent flow. The governing equations for the flow in the saturated zone and overland compartment of the model are further described in Appendix P.

# 9.3 Overall Setup of the Steady State Regional-scale Model

The model domain is equivalent to the model area mentioned earlier. The horizontal discretization is set to 1 km x 1 km based on an evaluation of computational times versus the need for a certain level of detail of model outputs.

The vertical discretization is 1 computational layer, extending from the topographical surface down to the defined lower level of the freshwater lens, i.e. the halocline.

As input for lower level of the aquifer a grid file of the halocline is made from a  $2^{nd}$  degree polynomial trend surface interpolation of point values computed by the fitted analytical model from Chapter 4 based on measured depths to the halocline. This does not give the accurate location of the halocline, but is a better estimate than a uniform surface.

As input for the topographical relief of the model area the SRTM topographic map is used (USGS, 2004). As a consequence of the horizontal discretization of the model the topographical data has been resampled to a coarser resolution than the 90 m resolution of the original data using the Nearest Neighbour averaging algorithm.

As mentioned, the unsaturated zone is neglected, and is thus assumed not to have an impact on the groundwater flow in the system. This is acceptable in a steady state system since the unsaturated zone is highly permeable and thus has limited retention capacity. However, overland flow is included according to the conceptual understanding of the system as there are inundated areas in the model area.

The precipitation data are annual average values from IWMI (2006) expressed in mm/day computed from monthly totals of the median precipitation. The horizontal discretization of the model means that the IWMI precipitation data used have received an artificially finer discretization than the 10 arc minutes (~16 km at Yucatan latitudes) that the data were originally in.

Infiltration fraction has been set to 1 as the amount of recharge is regulated by setting the recharge as a fraction of the precipitation.

The recharge is, as mentioned, estimated to range from 15% to 60% of the precipitation input. The model has been run with different recharge fractions to allow for evaluation of the model and the aquifer characteristics in the entire range of recharge estimates.

The geological map from INEGI (no year) with eight different geological units has been digitized, however it does not cover the entire model area and it has therefore been integrated into the USGS map of French and Schenk (1997) with four different geological units covering the entire Yucatan Peninsula. These latter data seem to originate from the work of Weidie (1985, cited in Beddows, 2004). In reality only two of the units from the USGS map cover the remainder of the model area (the Pliocene-Miocene unit and the Oligocene/Eocene unit). These units are assigned the same characteristics as the adjacent equivalent units of the INEGI map.

The model will be used to investigate whether different hydraulic conductivities can be expected for different parts of the model area. In this case the different geological units are divided into three categories of horizontal hydraulic conductivities, a high, medium and a low category, based on criteria described earlier. Since hydraulic conductivities are log-normally distributed, the difference factor between the three *K*-values is set to 10 as a minimum. A difference factor of minimum 10 is also used when investigating the effect of high permeability zones.

The vertical hydraulic conductivity is mainly relevant if there are several computational layers in the model; however it is also relevant for infiltration and overland flow. The vertical conductivity is generally assigned the same value as the horizontal.

The specific yield expresses the volume of water that can be drained from a unit volume of an unconfined aquifer at the force of gravity at a unit drop in hydraulic head. It is only relevant for transient models. The value has been set to 0.1 (dim. less). The specific storage coefficient is not used in these model runs, because it refers only to cells whose top surface is below the water table, of which there are none in our model since there is only one layer of cells. The specific storage coefficient has therefore just been assigned a value of  $0.2 \text{ m}^{-1}$ . The porosity of the geology is relevant in relation to the particle

tracking which will be carried out. Based on the porosity values found for the area and mentioned in Chapter 2, the porosity of the aquifer has been set to 0.3 (dim. less).

The initial potential head has been divided into four different zones parallel to the coast, which have been assigned increasing values inland (arbitrarily set to 4, 6, 9 and 15 m above mean sea level based on the expected order of magnitude of the heads in the areas in question). This has been done to make the model stabilize faster.

The saturated zone matrix modelling is calculated with the finite difference method and the Preconditioned Conjugate Gradient (PCG) solver is used, with no under-relaxation (see Appendix P for description of equations). Since it was found during the pre-thesis that the steady state version of the PCG solver failed to converge for our model setup, the steady state model in this thesis also uses the transient version of the solver, but with annual average precipitation data as input and run until heads are stable, so that it is in effect a steady state model. Steady state is achieved after about 15 years. The storing time steps has been set to 4800 hours.

The particle tracking has been run for a constant flow field using the steady state flow conditions resulting from the modelling of each scenario. For the particle tracking the effective porosity has been set to 0.3 (dim. less). Dispersion has not been taken into account, so the particle tracking is conservative, and actually a larger spread than that seen from the particle tracking results can be the case. Particles have been placed in the whole the model area and traced to within the borders of the Sian Ka'an Biosphere Reserve to delineate the catchment. MIKE SHE's particle tracking routine can only trace particles when they are within the saturated zone. Thus, particles moving to the overland flow compartment will be removed from the model domain (DHI, 2005a). Vertical correction has been specified in the particle tracking to ensure that only a limited amount of particles leave the saturated zone and move to the overland compartment when the thickness of the aquifer is reduced. Initially, the particles have been distributed randomly within each computational cell.

# 9.4 Steady State Regional-scale Model Scenarios

To test various hydrogeological hypotheses several model scenarios are set up. Firstly, a porous medium model consisting of only the aquifer compartment has been developed – this will in the following be called the SZ-model (saturated zone model). This is the Baseline model that other scenarios will be held up against. The overland flow component is omitted during the calibration of the model since it greatly increases the simulation time, but is added afterwards and evaluation of the performance of the different scenarios will be based on scenarios that include overland flow.

The model is calibrated against measured heads averaged over a 10 km x 10 km grid (see Chapter 5 for data processing of the raw data). This has reduced the error of the data while still maintaining a level of detail that allows for evaluating if the model is able to reproduce the geographical variations/contours in head pattern. The averaged heads dataset has been analysed for statistical outliers in Matlab, whereby two data points were eliminated. The averaged heads dataset with standard deviations and the two identified outliers can be seen in Figure 9.1. The hydraulic conductivities of the geological units are the parameters which may be varied in the calibration of the model to these data.



**Figure 9.1**.Observed heads averged over a 10 km x 10 km grid and standard deviations. Where more observations have been present in one grid cell the standard deviations have been calculated. Where only one observation has been present in one grid cell the standard deviation has been set to  $\pm 5$  m, which is an informed guess. The two points highlighted by red arrows are outliers identified with a statistical analysis in Matlab.

The location of the points where averaged head values have been calculated for, have been added to the detailed time series output function in MIKE SHE, which gives opportunity for comparing the observed and the modelled head elevations for each individual point. The model fit is evaluated with respect to the mean square error (MSE) weighted with the standard deviation of the head values as expressed by Equation 5.1 in Chapter 5.

First, it has been investigated whether the suggested division into three zones of different hydraulic conductivity could be verified by the model. This has been done by first calibrating the model with the assumed three hydraulic conductivities (maintaining a minimum difference factor of 10 between the *K*-values of the different units) and then comparing the goodness of fit to the equivalent for a model with uniform hydraulic conductivity of the model area. This test showed that the model with a uniform geology resulted in the best fit (MSE<sub>1K</sub> = 2.11 (dim. less) compared to a MSE<sub>3K</sub> = 2.25).

Another scenario with different hydraulic conductivity has been tested. Since it is expected that the low permeability 'ejecta' units that are distributed all over the model area and the low permeability Quaternary deposits around the wetlands may not extent all the way through the computational layer and may perhaps not even reach it, it is also tested if a scenario that takes this into account performs better than the scenario with uniform geology. Therefore, these assumed low permeability units are assigned horizontal hydraulic conductivities similar to the surrounding geological units and only lower vertical hydraulic conductivities. The units with medium and high hydraulic conductivities are the same. The

resulting fit (MSE<sub>2K</sub> = 2.18) is slightly better than the scenario where low permeability was assumed in the entire extent of the computational layer, but still not as good as the fit for the uniform geology scenario.

These tests show that the current data available for calibration of the model cannot justify using different K-values for the different geological unit. Therefore, in the further modelling of this present project, the uniform geology is maintained. However, it cannot be ruled out that improved calibration data can change this situation.

The scenarios listed in Table 9.1 have been set up and calibrated.

01 SZ	Saturated zone flow
02 SZ + HPZ	Saturated zone flow including high permeability zones (HPZ) as identified in Chapter 6
03 SZ + LPZcoast	Saturated zone flow including a low permeability zone (LPZ) along the entire coastline
04 SZ + HPZ + LPZcoast	Saturated zone flow including high permeability zones and a low permeability zone along the entire coastline
05 SZ + LPZtulum	Saturated zone flow including a low permeability zone along the coastline at the Tulum area (i.e. between the northern border of Sian Ka'an Biosphere Reserve and the model area's northern boundary)
06 SZ + HPZ + LPZtulum	Saturated zone flow including high permeability zones and including a low permeability zone along the coastline at the Tulum area (i.e. between the northern border of Sian Ka'an Biosphere Reserve and the model area's northern boundary)
07 SZ + HPZ + Holbox	Saturated zone flow including high permeability zones and the Holbox fracture zone. Note that no in- or outflow to and from the model area through the Holbox fracture zone is included in this scenario
08 SZ + HPZ + Perry fault	Saturated zone flow including high permeability zones and the fault suggested by Perry <i>et al.</i> (2002)
09 SZ + HPZ + Rio Hondo	Saturated zone flow including high permeability zones and the possible Rio Hondo fault zone continuations mentioned in Chapter 2
10 SZ + HPZ + Holbox, "Perry", Rio Hondo	Saturated zone flow including high permeability zones and the continuations of the Holbox, "Perry" and Rio Hondo faults and fracture zones

 Scenario name
 Features included

The results of the calibration can be seen in Appendix Q and in the DVD-appendix. Selected model outputs will be presented in the following for models that include the overland flow component.

It has been found that the 2D model gives a lower MSE (weighted with the standard deviation) of 2.11 (dim. less), compared to the analytical model from Chapter 5 which gives an MSE of 2.76 (dim. less), when modelling the same points at the same distance from the coast with the two models. Thus, a 2D model improves the description of the aquifer compared to a 1D model, as expected, but due to the low

quality of the data for calibration the improvement in model fit is not dramatic. In Appendix R the resulting heads from the regional-scale hydrological model have been plotted against the observed values and compared with a similar scatterplot from the 1D analytical model. The better fit is however not obvious from these plots since the standard deviations blur the picture.

# 9.5 Results

The prime purpose of developing the regional-scale hydrological model is to delineate the catchment of the Sian Ka'an Biosphere Reserve and to evaluate typical traveling times from areas of particular interest to Sian Ka'an. Such knowledge can support and guide management initiatives to protect the waters that feed into the reserve. In addition, the runs with the regional-scale hydrological model have been made in order to find out which areas it is important to study further in order to improve the description of the regional groundwater flow in the area.

From the outcome of the experiments with the conduit-matrix model and the equivalent SHE-model it has been found that a first estimate of the high-permeability value of regional-scale structures in the aquifer could be  $K_{HPZ} = 4$  m/s, as seen in Chapter 8. Thus, first results of running the various scenarios of the model with this value are presented below. Subsequently, the impact of a different  $K_{HPZ}$  in the structures is investigated. Finally, the effect of increased evapotranspiration and evaporation from plants and open water bodies in the areas with overland flow is investigated, in order to evaluate the possible impact of such an additional water sink in the model area, which has otherwise not been taken into consideration in the modelling.

Unless otherwise is stated, all shown results are for an input recharge of 30% of mean annual precipitation.

#### 9.5.1 <u>Regional Models with *K*<sub>HPZ</sub> = 4 m/s</u>

All the scenarios mentioned in Table 9.1 have been tested with the developed regional-scale model. The identified structures have been assigned a  $K_{HPZ}$  of 4 m/s in accordance with the estimate based on the conduit-matrix model experiments. The  $K_{SZ}$ -values calibrated for each of the scenarios are seen in Appendix Q but range from 0.2 m/s for the Baseline model, with a uniform geology, to 0.1 m/s for Scenario 10 with all the possible structures.

Figure 9.2 and Figure 9.3 illustrate the location of the structures/high permeability zones of the various scenarios.

#### 9.5.1.1 Occurrence of Overland Flow

The regional-scale hydrological model results in an occurrence of overland flow as displayed in Figure 9.4. This pattern is the same in both the Baseline case and all the scenarios tested.

It is clearly seen that the overland water is generally located in the Sian Ka'an Biosphere Reserve as well as in the area south of the reserve, where flooded areas are also visible from Landsat imagery and from

the map of ITMB (2005). There is an excellent correspondence with the places the model yields overland water, and the places which are indicated as flooded areas on the map of ITMB (2005). In addition, Lake Bacalar, Lake Nohbec, Lake San Felipe and Lake Ocom are clearly seen as overland water in the model output. Also the lakes around Lake Kaná are seen.



**Figure 9.2**. The structures identified in Chapter 6 and which are included in Scenarios 2, 4, 6 and 10 (left). The possible fault/fracture structures identified from the literature (right) and which are individually included in Scenario 7, 8 and 9, respectively, and which are all included in Scenario 10. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andres Quintana Roo.



All possible structures, as included in Scenario 10

**Figure 9.3**. All the possible structures/high permeability zones. These are the structures included in Scenario 10. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andres Quintana Roo.


Figure 9.4.. Ocurrence of overland water in the regional scale hydrological model. The legend shows depth of overland water in meters. The units of x-axis and y-axis is UTM coordinates with WGS84 ellipsoid, and thus meters. Thus, it is seen that the occurrence of the wetlands of Sian Ka'an and many of the flooded areas located south of the reserve is controlled by topography and the groundwater level, and the results show that the topography is well described, which is why the model captures the real occurrence of overland water well. The intermittently flooded areas inland in the model area are not captured by the steady state model, which would also not be expected since they form in the rainy season and thus not with averaged precipitation as an input.

According to output of the Baseline model, the average depth of all the overland water is 0.88 m, with a minimum of 0.00 m and a maximum 11.41 m. The drastic maximum value occurs at Lake Ocom and is due to a very low topographic value in these cells. Thus, the maximum depths of the overland water should be viewed with some reservations, since the overland water depth is given with respect to the topographical level of the SRTM dataset, which may have pixels with values which do not correspond to the values of the surrounding terrain. However, an average water level depth of 0.88 m seems reasonable. If filtering away all values above 3 meters, assuming that these are due to topographical artifacts, the average depth of the overland water is 0.93 m, i.e. practically the same level. Inside the Sian Ka'an Biosphere Reserve, the number of cells with overland water corresponds to an area of 1887 km<sup>2</sup>. This corresponds to 36% of the total area of Sian Ka'an (5280 km<sup>2</sup>), and is thus in excellent agreement with the fact that wetlands are known to constitute about 1/3 of the area of the reserve (CONANP, 2006). The average overland water depth inside the reserve is 0.83 m, according to this Baseline model output, and corresponds rather well with our general field observations. It is also in general accordance with the values measured by Chiappa-Carrara et al. in lagoons of Sian Ka'an distributed along the coast north of Punta Allen (min.: 0.55 m, max.: 2.1 m, average: 0.93 m; measured in May 1997) (data from Chiappa-Carrara, pers. comm., 2006).

It has been tested if the depth of overland water in the model area is sensitive towards the vertical hydraulic conductivity in these areas. Given the estimated lower permeability of the ejecta and Quaternary layers, the vertical hydraulic conductivity of these layers has therefore been varied within reasonable values from the literature. However, it was found that the model is not sensitive towards changes in this parameter, and it has therefore been chosen to set vertical and horizontal hydraulic conductivity to a constant in all geological units. The test also showed that this parameter cannot be used to regulate the depth of the overland water in the model. Further details may be found in Appendix S.

#### 9.5.1.2 Groundwater Heads and Catchment of Sian Ka'an

The Baseline model resulted in a groundwater head pattern which is seen in Figure 9.5. The heads range from 10.8 m in the most south-western part of the model area to 0 m at the coast as specified there. The contour lines are generally seen to be parallel to the coastline. Head gradient along the flow line A is  $5 \cdot 10^{-5}$  (dim. less) (i.e. 500 mm/10 km), head gradient along flow line B is  $7 \cdot 10^{-5}$  (dim. less) (i.e. 700 mm/10 km), and is a bit steeper along flow line C, namely  $1.1 \cdot 10^{-4}$  (dim. less) (i.e. 1100 mm/10 km). All values are in the same range as those found by Beddows (2004) for the northern part of the model area (presented in Chapter 8). The gradients are seen on the figure to become somewhat steeper closer to the coast as is the case for a typical island/peninsula freshwater lens.



Figure 9.5. Resulting head pattern of the Baseline model. Dashed lines indicate flow lines for which hydraulic gradients are reported in the text. The legend unit is m.a.m.s.l.

When the high permeability areas of the scenarios are designated a  $K_{HPZ} = 4$  m/s, the resulting head pattern is similar to that of the Baseline case, with head contour lines generally parallel to the coast. This means that the overall flow pattern of all the scenarios is basically the same. This is illustrated in Figure 9.6, which show the catchment of Sian Ka'an resulting from the Baseline model and the Scenario 10 model, which includes all the possible structures identified. These catchments show that in these models the flow is primarily perpendicular to the coast, and the flow patterns are overall coast-controlled. These figures also show that in these models it takes roughly 400 years for the water from the most inland parts of the catchment to reach the Sian Ka'an Biosphere Reserve. None of these scenarios show that water from the area encompassed by the Tulum development plan (purple outline on the figures) flows towards Sian Ka'an.



**Figure 9.6**. The catchment of Sian Ka'an when using the Baseline model (left) and in Scenario 10 with  $K_{HPZ} = 4$  m/s (right). The colours show transport time of a water particle from the location to the Sian Ka'an area. The legend unit is years. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andres Quintana Roo.

However, although the overall catchment is practically the same in all scenarios with  $K_{HPZ} = 4$  m/s, there is a difference in the flow pattern within a shorter time frame. This is illustrated in Figure 9.7, which show the 10-year travel distances of water particles in the model area towards Sian Ka'an, for the Baseline model and the Scenario 10 model with  $K_{HPZ} = 4$  m/s. The figure shows that in the Baseline case the average transport time for a water particle from Felipe Carrillo Puerto (upper black dot) to Sian Ka'an is 8 years (ranging from 7-10 years)<sup>14</sup>, while in Scenario 10 it only takes 5 years (range: 4-8 yrs) for a water particle to move between the same two areas. It is interesting to look at Felipe Carrillo Puerto since it is a larger town in the region (18,000 inhabitants in 2000<sup>15</sup>), located only 15 km from the boundary of the Reserve. In addition, it is interesting to look at the water transportation time from the area around Andres Quintana Roo (lower black dot), since this area is described as an agricultural area which could potentially threaten the water quality of Sian Ka'an (UNEP WCMC, 2001). As seen, water does not flow from this area to Sian Ka'an in the Baseline case, but in Scenario 10 water from the Andres Quintana Roo area flows to Sian Ka'an within only 10 years, according to the model (range: 6-14 yrs, since there is a large scatter in travel times in Scenario 10).

Figure 9.7 show that when structures are included in the model and  $K_{HPZ}$  is 4 m/s, only the structures identified in Chapter 6 impact the shape of the short-term catchment, while the fault suggested by Perry

<sup>&</sup>lt;sup>14</sup> Due to that the travel times have a rather high degree of scatter in the model outputs, travel times have been taken as the average travel time value for the 9 cells (9 km<sup>2</sup>) around the location of Felipe Carillo Puerto and Andres Quintana Roo. The range of the cell values are reported in brackets.

<sup>&</sup>lt;sup>15</sup> According to their website (FCP, 2006), but judging from the visual impression of the town and talks with people in the area it is likely that the number of inhabitants is larger than this now in 2006.

*et al.* (2002) and the continuations of the Rio Hondo faults hardly change the extent of the catchment. The Rio Hondo fault extensions are only seen to impact the catchment up to 10 km from the southern boundary when they are included in Scenario 9 and 10. Beyond this, the water drains southwards instead, to the Bay of Chetumal.

The amount of recharge is an important control on the transportation times of the water in the catchment, but is unfortunately a parameter which currently is very vaguely quantified. Figure 9.8 shows the impact on traveling times if recharge is the maximum reported in the literature, namely 60%. It is seen that in the Baseline case, traveling time from Felipe Carrillo Puerto to Sian Ka'an is roughly halved to 4 years.



**Figure 9.7**. 10 year transport times in the Baseline model (left) and in Scenario 10 with  $K_{HPZ} = 4$  m/s (right). The legend unit is years. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andres Quintana Roo.



Baseline, 60% recharge

**Figure 9.8**. 10 year transport times in the Baseline model when recharge is 60% of mean annual precipitation. The legend unit is years. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andres Quintana Roo.

Figure 9.9 shows the output from the particle tracking when particles are placed around Felipe Carrillo Puerto and Andres Quintana Roo, and traced to their outlet. This simulates the transport of pollution from these two locations to the coast. The particle tracking in the Baseline case shows how the transport of pollution from Felipe Carrillo Puerto is not very spread out but flows in a line perpendicular to the coast following the head gradient. The pollution plume from Andres Quintana Roo bends towards the Bay of Chetumal in the Baseline case, and is slightly more spread out, since flow lines in the area are not solely in one direction. However, when all possible structures are included, in Scenario 10, the spread of the pollution plume looks markedly different, as seen in Figure 9.9 (right). It is seen how structures to a large degree control and concentrate the spread of pollution. It is also seen that in order to properly understand pollution spread in the area it is of utmost importance to obtain more knowledge about the structures, especially their locations and their potential for water conveyance.



Baseline

Scenario 10,  $K_{HPZ}$  = 4 m/s

**Figure 9.9**. Visualization of transport of pollution from Felipe Carrillo Puerto (northern black dot) and Andres Quintana Roo (southern black dot) in the Baseline case (left) and in Scenario 10 when  $K_{HPZ} = 4$  m/s. The legend unit is relative and thus just indicates large transportation of water particles through each cell (blue), or low amount of particles (red).



**Figure 9.10**. Location of the potential low permeability zone at Tulum (blue line), as used in Scenario 5 and 6. This stretch is 30 km long. The gray lines outline the potential high permeability zones identified in Chapter 6; the red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve.

One scenario resulted in a different catchment than the rest. This was the Scenario 6, which includes the high permeability zones identified in Chapter 6 as well as a low permeability zone at the coast near Tulum. Figure 9.10 shows the location and extent of this low permeability zone, which has been defined as 30 km long and defined as 1 km wide, as this is the width of one grid cell in the model. As seen in

Figure 9.10 the low permeability zone has been defined to border the high permeability zone defined in the Pleistocene geology around Tulum. The hydraulic conductivity of the high permeability zones is here still defined to be  $K_{HPZ} = 4$  m/s. However, the order of magnitude of the hydraulic conductivity in the low permeability zone ( $K_{LPZ}$ ) is not known. Therefore, two possibilities have been examined:

<u>Scenario 6 Type 1</u> is where the difference between the matrix hydraulic conductivity,  $K_{SZ}$ , and the  $K_{LPZ}$  is one order of magnitude, i.e.  $K_{LPZ} = 1/10 \cdot K_{SZ}$ . The best fit values have for that case been found to be  $K_{LPZ} = 0.017$  m/s and  $K_{SZ} = 0.17$  m/s. This scenario yields an MSE of 2.08.

<u>Scenario 6 Type 2</u> is where it is assumed that  $K_{LPZ} = K_{SZ}$ . Thus, the high permeability zone at Tulum separates the coastal and the inland area, which are assumed to in effect have the same hydraulic conductivity. This model has been calibrated to have  $K_{LPZ} = K_{SZ} = 0.14$  m/s, yielding an MSE of 2.12.

Figure 9.11 shows the resulting catchments of Sian Ka'an and Figure 9.12 shows a close-up of the area near Tulum. It is seen that for the Type 1 scenario, the reduced hydraulic conductivity at the coast creates a barrier and thus forces water from the area covered by the Tulum urban development plan to Sian Ka'an. The traveling time from the area of the Tulum urban development plan to Sian Ka'an ranges from only 1 year to 8 years in this scenario, with an average value of 3 years. In the Type 2 scenario, no water is modelled to travel from the Tulum urban development plan area to Sian Ka'an.

The coastal outflow through the low permeability zone is quantified to be  $0.65 \text{ m}^3$ /s pr. km coast for Scenario 6 Type 1, while it is  $1.86 \text{ m}^3$ /s pr. km coast for Scenario 6 Type 2. These values may be compared with values from the literature to evaluate how realistic the two scenarios are.

Based on the average annual outflow rates for two outlet points on the Caribbean Coast, which are linked to larger cave systems, Beddows (2004) estimated outflow near these cave systems to be 0.99 m<sup>3</sup>/s pr. km coast and 1.83 m<sup>3</sup>/s pr. km coast (at Casa Cenote 6 km north of Tulum, and Xel Ha, respectively, and covering 3 and 4 km of coastline, respectively). These values thus represent coastal stretches with significant cave development. In addition, Hanshaw & Back (1980) estimated coastal discharge to be on average 0.27 m<sup>3</sup>/s pr. km for their study area in the northern part of the Yucatan Peninsula, covering 1,100 km of coastline, i.e. as an averaged value for stretches with and without large coastal outflows.

The values of both the Scenario 6 Type 1 and Type 2 coastal outflows are thus in the same range as values reported in the literature. The Type 2 scenario outflow is the same as the largest found by Beddows (2006) in the region while the Type 1 scenario outflow is still double the size of the value estimated by Hanshaw & Back (1980) and thus also seems as a realistic value for an outflow from an area with such significant cave development as that near Tulum. Thus, it cannot be excluded that the critical pattern shown by the Type 1 scenario can be the actual case in the model area. This is especially notable since in this scenario, the possibility of caves directly connecting the Tulum development plan area and Sian Ka'an has *not* been taken into consideration -a fact which could then further reduce the travel time of water between the two areas. Whether the water from the Tulum area reaches Sian Ka'an however depends on the nature as well as the southwards extent of the low permeability zone, since, as seen more clearly in Figure 9.13 the degree of southward flow is strongly controlled by this extent. Thus, it must be investigated whether the low permeable zone exists and how far south it stretches, since, if it stretches further south than modelled here, areas further south in Sian Ka'an will be impacted, and if it does not have as large an extent as used here, Sian Ka'an will not be impacted. The extent of the low permeability zone could possibly be related to the extent of the Pleistocene geology for which the southern boundary is currently uncertain, as discussed in Chapter 2 and Chapter 6.



**Figure 9.11**. The resulting catchment of Sian Ka'an in Scenario 6 Type 1(left) and Type 2 (right). The colours show transport time of a water particle from the location to the Sian Ka'an area. For this scenario it is seen that in the Type 1 case, water flows from the Tulum urban development plan area (purple outline) to Sian Ka'an . The legend unit is years. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andreas Quintana Roo



**Figure 9.12**. A close up of area near Tulum, for the same scenarios as shown in Figure 9.11. Figure 9.10 shows from where in the model outline this close-up is taken. The legend unit is the same for the two images and is years travel time to Sian Ka'an.



**Figure 9.13**. A close up of area near Tulum with particle tracking showing the flow direction of water from the Tulum development plan area. The legend is relative with no unit, so that a high number (blue) indicates much water passing through this area, and a low number (yellow to red) indicates less water passing through this pixel.

#### 9.5.2 Regional Models with Increased K<sub>HPZ</sub>

The value of 4 m/s for  $K_{HPZ}$  used in the previous section is an estimate. In order to evaluate how realistic this value is, and whether other values could be realistic too for the hydraulic conductivity of the high permeability zones, the flow magnitudes resulting from the Scenario 10 simulation presented previously have been analyzed and compared to Scenario 10 run with  $K_{HPZ} = 8$  m/s and  $K_{HPZ} = 20$  m/s, i.e. a  $K_{HPZ}$  of double the size as previously, and a  $K_{HPZ}$  two orders of magnitude larger than the hydraulic conductivity of the matrix, respectively.

Table 9.2 shows groundwater flow magnitudes in the x- and y-direction at 5 selected points in the model area for these three Scenario 10 runs. Note that negative values indicate that flow is inland (x-values) or southward (y-values) and vice versa. The five points have been selected in order to give an overall picture of the flow magnitudes. Thus, the Payo Obispo point (# 1) and the Ocom point (#2) are chosen because they are located in areas with high flow in the structures. The two Vigia Chico points (#3 and #4) have been chosen because they are located in one of the Rio Hondo fault extensions and may possibly be connected to the Caapechen cave system. The Andres Quintana Roo point (#5) is chosen also because it is located on a Rio Hondo fault extension. In addition, the general magnitude of the matrix flow has been read. Figure 9.14 shows the location of the five selected points, and gives an example of how the distribution of groundwater velocities in the x- and y-direction may look.

Flow velocity in x/y direction [m <sup>3</sup> /s]	$K_{HPZ} = 4 \text{ m/s}$		$K_{HPZ} = 8 \text{ m/s}$		$K_{HPZ} = 20 \text{ m/s}$	
	Х	У	х	у	х	у
#1 Payo Obispo	11.6	0.02	15.9	-0.02	26.9	-0.1
#2 Ocom	10.7	0.1	14.9	0.1	31.0	-0.1
#3 Vigia Chico 1	1.9	-0.1	3.1	-0.1	9.1	-0.02
"						
#4 Vigia Chico 2	3.4	-0.5	5.0	-0.3	11.1	-0.1
#5 Andres Quintana Roo	2.8	2.7	4.1	4.7	10.9	14.7
Matrix	0.2-0.5	-0.05-0.1	0.2-0.5	-0.05-0.1	0.2-0.5	-0.05-0.1

**Table 9.2**. Flow magnitudes in x- and y-direction, respectively, read in the 5 selected points and overall for the matrix. The values are for Scenario 10, run with three different  $K_{HPZ}$ -values.



**Figure 9.14**. Example of flow magnitude pattern in the x- (left) and y-direction (right). This figure is for when  $K_{HPZ} = 8$  m/s. Orange/red values indicate negative flows, i.e. that flow is in the inland or southward direction, respectively. The numbers on the left figure indicate the five selected points for which flow velocities have been read. 1: Payo Obispo; 2: Ocom; 3: Vigia Chico 1; 4: Vigia Chico 2; 5: Andres Quintana Roo. The legend unit is m<sup>3</sup>/s.

Here only flows in the x-direction will be described. As seen from the table, the flows in the matrix are of the same magnitude for the three cases, namely in the order of  $0.2 - 0.5 \text{ m}^3/\text{s}$ . The difference in flows is however seen on the flows in the x-direction at the five points. When  $K_{HPZ} = 4 \text{ m/s}$  the flows in the Rio Hondo fault extensions range from 1-3 m<sup>3</sup>/s, while in the high flow areas flow is 11-12 m<sup>3</sup>/s. When  $K_{HPZ} = 8 \text{ m/s}$  the flows in the Rio Hondo fault extensions are slightly larger, and range from 1-5 m<sup>3</sup>/s, while in the high flow areas flow is 15-16 m<sup>3</sup>/s. Finally, when  $K_{HPZ} = 20 \text{ m/s}$  the flows in the Rio Hondo fault extensions range from 3-11 m<sup>3</sup>/s, while in the high flow areas flow is 27-31 m<sup>3</sup>/s.

We do not have much knowledge about the possible magnitude of flows in high permeability areas in the model area. However, the highest reported cave flow value which we have encountered is the estimated 13 m<sup>3</sup>/s for the Caapechen system, which may even be larger than this, as mentioned in Chapter 8. Thus, the flows simulated by the model when  $K_{HPZ} = 8$  m/s and  $K_{HPZ} = 20$  m/s do not seem unrealistic, and thus

a hydraulic conductivity of the high permeability areas of up to two orders of magnitude larger than the hydraulic conductivity of the matrix cannot be excluded.

Therefore, the regional model has been run also with these  $K_{HPZ}$  –values in order to see what effect this has on the catchment. The results of running the Scenario 10 with these values are shown in Figures 9.15 and Figure 9.16. As seen, when  $K_{HPZ} = 8$  m/s the overall catchment for Sian Ka'an covers more or less the same area as when  $K_{HPZ}$  was 4 m/s; it only extends slightly further south in the middle of the model area (cp. with Figure 9.6 (right)). However, using  $K_{HPZ} = 20$  m/s dramatically changes the catchment of Sian Ka'an because the higher permeability of the structures means that water from further south and inland also ends up in Sian Ka'an. These southern areas are known to be agricultural areas where the land use is more intensive than in the middle and northern parts of the model area. Figure 9.16 shows the 10-year catchment and shows that the catchment stretches much further south towards the agricultural areas in this case even when only considering travel times  $\leq 10$  years.



**Figure 9.15**. The catchment of Sian Ka'an in Scenario 10 when using  $K_{HPZ} = 8$  m/s (left) and  $K_{HPZ} = 20$  m/s (right). The colours show transport time of a water particle from the location to the Sian Ka'an area. The legend unit is years transport time to Sian Ka'an. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andreas Quintana Roo.



**Figure 9.16**. 10 year transport times in Scenario 10 when using  $K_{HPZ} = 8$  m/s (left) and  $K_{HPZ} = 20$  m/s (right). The colours show transport time of a water particle from the location to the Sian Ka'an area. The legend unit is years transport time to Sian Ka'an. The purple outline is the area encompassed by the Tulum urban development plan. The red line indicates the model area; the green line outlines the Sian Ka'an Biosphere Reserve. The northern black dot indicates the position of the town Felipe Carrillo Puerto, the southern black dot is the location of the agricultural area Andreas Quintana Roo.

In Scenario 10, travel times from Felipe Carrillo Puerto to the Sian Ka'an Biosphere Reserve is 5 years (range: 3-9 yrs) when  $K_{HPZ} = 8$  m/s and 3 years (range: 2-7 yrs) when  $K_{HPZ} = 20$  m/s. Travel times from Andres Quintana Roo to Sian Ka'an is 10 years (range: 4-16 yrs) when  $K_{HPZ} = 8$  m/s and 6 years (range: 1-13 yrs) when  $K_{HPZ} = 20$  m/s. Figure 9.17 shows the pattern of the pollution plume from the two towns in Scenario 10 when  $K_{HPZ} = 20$  m/s. It is seen that, not surprisingly, when the hydraulic conductivity of the structures is increased, the structures will to a very large degree control the flow of the pollution plume, and when comparing with Figure 9.9 it is seen that the pollution is transported much further when  $K_{HPZ}$  is high. It is thus clear that if one wants to know the impact area of a possible pollution, determining the location and characteristics of the structures becomes extremely important.

#### 9 - Regional-Scale Hydrological Model



**Figure 9.17**. Visualization of transport of pollution from Felipe Carrillo Puerto (northern black dot) and Andres Quintana Roo (southern black dot) in Scenario 10 when  $K_{HPZ} = 20$  m/s. The legend unit is relative and thus just indicates large transportation of water particles through each cell (blue), or low amount of particles (red).

Figure 9.18 gives an example of the head pattern when the  $K_{HPZ}$  is increased. The figure is for when  $K_{HPZ}$  is 20 m/s, but the values of 4 m/s and 8 m/s has not been seen to give a significantly different picture. It is seen that the general head pattern when  $K_{HPZ}$  is 20 m/s is still dominantly coast controlled. The structures generally do not create a noticeable change in the overall head pattern, even when the hydraulic conductivity of the structures is relatively large as in this case. Only exception is south of Sian Ka'an in one of the Rio Hondo extensions, where a drawdown and thus change in head pattern is seen when comparing with the head pattern of the Baseline case shown in Figure 9.5. This latter pattern is also not seen when  $K_{HPZ}$  is 4 m/s. Thus, the structures can largely influence the catchment to Sian Ka'an even when their impact can hardly be seen on the head pattern. The little influence on the overall head pattern is due to the general high hydraulic conductivity of the aquifer and the strong gradient that the zero head at the coast creates.

However, that the structures *do* change the head pattern *locally* compared to when they are not included, can be seen from Figure 9.19 which shows the difference in the steady state heads resulting from the Scenario 10 with  $K_{HPZ} = 20$  m/s and the Baseline case. The expected local decrease in heads is seen over the areas where there are structures. When  $K_{HPZ} = 20$  m/s the maximum head reduction compared to the Baseline case is -4 m over the structures, while when  $K_{HPZ} = 8$  m/s it is -3.5 m and when  $K_{HPZ} = 4$  m/s it is -3 m. These numbers only illustrate that, as expected, head decrease over structures is larger when the hydraulic conductivity of the structures is larger. However, these values do *not* show that the groundwater head is much lower over structures than the surrounding groundwater heads in the matrix. The drawdown over a structure has been seen from Figure 9.18 to not be discernable from the overall head pattern, and thus may be much less than 1 meter over a structure. Therefore, if a possible drawdown in groundwater heads over a structure should be measured in the real model area, the accuracy must be quite high.



**Figure 9.18**. Resulting head pattern of the Scenario 10 model when  $K_{HPZ} = 20$  m/s. Arrow indicates the only area where the head pattern is noticeably different from the Baseline case (cp. Figure 9.5). The egend unit is m.a.m.s.l.. Unit of x-axis and y-axis is UTM coordinates, and thus meters.



**Figure 9.19**. Difference in steady state heads between Scenario 10 with  $K_{HPZ} = 20$  m/s and the Baseline case. Negative values (green and blue areas) indicate that the steady state heads were higher in the Baseline case than in Scenario 10,  $K_{HPZ} = 20$  m/s. The unit of x- and y-axis is kilometers.

The Scenario 6 Type 1 model has also been run with  $K_{HPZ} = 20$  m/s. It was found that with such a high hydraulic conductivity in the structures, the same flow pattern as seen in Figure 9.12 (left) with flow from the Tulum development plan area is still seen, and the travel time is still 3 years (range: 1-8 years) as before. However, the outflow from the low permeable coastline is now 0.76 m<sup>3</sup>/s pr. km coastline, and thus increased compared to when  $K_{HPZ}$  was 4 m/s, but still a very realistic value. Therefore this scenario is also realistic.

#### 9.5.3 Regional Models with Increased Evapotranspiration from Wetlands and Swamps

The previously presented regional models have dealt with evapotranspiration loss by assuming that the evapotranspiration is a constant fraction of the precipitation throughout the model area, since recharge has been set to a constant percentage of the rainfall. However, in the actual model area, this may be a crude assumption which may especially not be valid in the wetland areas and close to the coast. In the wetland and flooded areas, water may be lost by direct evaporation from the open water bodies. In addition, in the wetlands the plant roots take up water directly from the saturated zone, and thus there is a loss of water directly from the aquifer via this pathway. As discussed in Chapter 2, direct uptake of water from the saturated zone may also take place from other trees and plants not belonging to wetlands, especially in the areas where the unsaturated zone is relatively thin, i.e. in the areas closer to the coast.

In order to include direct evapotranspiration (ET) from the saturated zone in the model, a simple first order approach has been implemented. Wells have been inserted in the model in the areas where overland flow has been found to occur – one well pr. pixel with overland water. Thus, the scenario considers the direct evaporation from open water bodies and the evapotranspiration from the wetland plants, but not from phreatophytic plants growning in an area with a thin unsaturated zone. The location of the inserted wells is shown in Figure 9.20. The abstraction rate from each well has been set to be the potential evapotranspiration rate (ET<sub>0</sub>) for the area. Thus, from the IWMI data the ET<sub>0</sub> has been read to be on average 1470 mm/year =  $4.7 \cdot 10^{-8}$  m/s. Since this is assumed to occur throughout each pixel, which each have a surface area of 1 km<sup>2</sup>, the abstraction rate for each well is set to 0.05 m<sup>3</sup>/s.



Figure 9.20. Black dots show the location of the pixels with overland flow and thus the location of the wells inserted to simulate areas with high evapotranspiration.

This scenario with additional ET has only been run for the Scenario 10 conditions where all possible high permeability zones are included, to investigate the possible impact.  $K_{HPZ}$  has been set to 20 m/s. As seen in Figure 9.21 when taking this additional evapotranspiration into account, the groundwater heads in the areas with the increased ET becomes lower, as expected, compared to when this additional sink was not included. The impact is greatest south of Sian Ka'an near the Costa Maya coast, although the density of wells is not highest here. The reason must be because the aquifer is thinner here, due to the way the lower level has been specified in the model, as illustrated in Figure 9.22. Because of that, a larger area is impacted in this particular area by the set abstraction rate.

Figure 9.23 illustrates the head difference between when there is the increased ET loss in Scenario 10 with  $K_{HPZ} = 20$  m/s and the Baseline case. The circle in the figure indicates the area with increased drawdown due to the ET loss, compared to when increased evapotranspiration has not been taken into account (cp. Figure 9.19).

#### 9 - Regional-Scale Hydrological Model



**Figure 9.21**. Steady state head difference with wells (as a proxy for increased evapotranspiration) minus without wells. The legend unit is head difference in meters.



Figure 9.22. Lower level of the aquifer. The legend unit is m.a.m.s.l. The axis unit is UTM-coordinates, and thus meters.



**Figure 9.23**. Difference in steady state heads between Baseline case and Scenario 10 with  $K_{HPZ} = 20$  m/s and additional water removal by evapotranspiration in the areas with overland flow. Negative values (green and blue areas) indicate that the steady state heads were higher in the Baseline case than in Scenario 10,  $K_{HPZ} = 20$  m/s with "evapotranspiration". The axis unit is kilometers. The circle indicates area with increased drawdown compared to when increased evapotranspiration has not been taken into account (cp. Figure 9.18).

Including the increased ET loss is seen to influence the pattern of the groundwater heads in this case, as illustrated in Figure 9.24. It is seen that the increased ET implemented by the wells change the head pattern by creating lower heads especially in the southern half of the model area. (cp. with Figure 9.18).

However, despite the increased loss from ET, the observed head drawdowns resulting from the model and the observed change in head pattern, the ET implemented here is not seen to change the extent of the catchment which contributes with water to Sian Ka'an in the model. This is shown in Figure 9.25, which shows that in the models we have run, the increased ET implemented in the areas where there is overland flow, does not change the catchment. This is shown for both the Scenario 10 case with  $K_{HPZ} = 4$  m/s and  $K_{HPZ} = 20$  m/s.

However, although the models run here do not show a change in the catchment when additional ET is taken into account, the head drawdowns and change in head pattern show that it is important to quantify better the ET loss arising from water uptake by plants directly from the saturated zone. In addition, not only this ET loss from the wetlands and open water bodies, but also from the plants growing above a relatively thin unsaturated zone must be taken into account, since these can also potentially abstract significant amounts of water from the groundwater table. Furthermore, in order to evaluate the impact of such losses the actual thickness of the aquifer in the model area, and especially in Sian Ka'an and the coastal areas, they should be determined better and implemented in a more correct way in a future regional-scale model.



**Figure 9.24**. Steady state heads from wells, Scen 10, K is 20. Circle indicates the area where heads are especially lowered due to the increased water removal by ET. The legend units is m.a.m.s.l. The axis unit is UTM-coordinates, and thus meters.



**Figure 9.25.** The catchment of Sian Ka'an in Scenario 10 when including additional evapotranspiration loss, implemented via wells, and when using  $K_{HPZ} = 4$  m/s (left) and  $K_{HPZ} = 20$  m/s (right). The colours show transport time of a water particle from the location to the Sian Ka'an area. The legend unit is years transport time to Sian Ka'an.

## 9.6 Summary and Conclusions

The main purpose of the regional-scale model has been to delineate the catchment comprising the Sian Ka'an Biosphere Reserve and to determine travelling times from potential pollution sources to the Reserve, as this knowledge is essential for a sustainable management of the water resources in the area.

The presented model generally shows compliance with the regional characteristics of the aquifer, in that it is able to represent overland flow in areas that are known to be permanently inundated or consist of wetlands with average depths of  $\sim 0.9$  m. Also the lenticular shape of the aquifer with steeper gradients close to the coast and a clear coast-controlled flow pattern has been found by the model. Gradients in the model area have been found to be within the values mentioned in the literature.

A Baseline model only consisting of matrix flow has been compared with scenarios that include the potential high permeability zones identified in Chapter 6 as well as the extensions of major faults in the area assuming *K*-values of 4 m/s and 20 m/s, respectively, for these zones. The K = 4 m/s corresponds to a reasonable value found for the conduit in the conduit-matrix model presented in Chapter 8. Resulting flows for the two scenarios are 0.2-0.5 m<sup>3</sup>/s in the matrix, whereas the flow in the low flow structures (faults) are 1-3 m<sup>3</sup>/s and 3-11 m<sup>3</sup>/s, respectively and the flow in the high flow structures (identified in Chapter 6) are 11-12 m<sup>3</sup>/s and 27-31 m<sup>3</sup>/s, respectively. All of these flow magnitudes fall within currently available estimated flow magnitudes. Using a *K*-value of 4 m/s in the structures does not significantly change the size of the catchment, whereas a *K*-value of 20 m/s changes the catchment size significantly; however for both scenarios it is evident that the structures control head patterns as well as pollution spreading. Pollution from the nearby urban and agricultural areas of Felipe Carrillo Puerto and Andres Quintana Roo may reach Sian Ka'an in less than 10 years assuming a *K*-value of 20 m/s in the structures, whereas pollution from even more distant agricultural areas in the southern and central parts of the model area may spread to Sian Ka'an within the same time frame assuming a *K*-value of 20 m/s in the structures.

One of the model scenarios showed that water flowing through the area covered by the urban development plan for Tulum may reach the northern areas of the Sian Ka'an Biosphere Reserve in < 5 years if a low permeability zone is assumed in the near-coastal zone. This result appears despite the fact that a possible direct conduit connection has not been included in the model. How far into the reserve particles from Tulum are able to travel is controlled by the southwards extent of this zone. It should be noted that the actual extent and permeability of the coastal zone is not known and should therefore be investigated further. It can however also not be ruled out that water flowing southwards from Tulum will be captured by the Ox Bel Ha cave system and transported towards the Caribbean Sea without reaching Sian Ka'an. Also this should be investigated further in the future.

A scenario with increased evapotranspiration from wetlands and inundated areas due to assumed water uptake directly from the saturated zone has not been found to change the extent of the catchment in the current model. However, a change of head pattern was seen south of Sian Ka'an in an area where the freshwater lens is rather thin. It is recommended that the issue of phreatophytic evapotranspiration should be investigated further in the future. A reason why no change in catchment can be seen in the present model for this scenario may be due to the shape of the lower level of the aquifer not being defined correctly in the Sian Ka'an area.

The model has also lead to identification of fields that should be studied further, as they are necessary in order to construct a more representative model for the catchment and for more accurately being able to estimate the actual size of the fresh groundwater resource. This includes a more accurate estimation of recharge, as well as infiltration rates and storage capacity of the unsaturated zone, which may be important according to Beddows (2004).

# 10 Discussion and Perspectives

### 10.1 Discussion of Results in Relation to the Water Management Issues

It is clear that there are several potential threats to the fresh groundwater resources in the model area; in particular the suggested development in Tulum, the potential groundwater pollution from Felipe Carrillo Puerto and that of the agricultural areas in the southern-central part of the model domain. This combined with the general vulnerability of the aquifer emphasizes the need for proper water management in the area.

In the present project we have investigated whether the Ghyben-Herzberg relationship is valid for describing the aquifer of study. The data indicate that the Ghyben-Herzberg relationship may hold in the inland parts of the model area while it is not necessarily valid on the first 10 km from the coast, as found by Beddows (2004). These findings are important in relation to quantifying the thickness of the freshwater lens and thus the magnitude of the fresh groundwater resource available. In addition, it is important to know more about the controls on the vertical extent of the freshwater lens if the effect of extensive groundwater pumping for water supply should be properly evaluated. The data on the vertical extent of the freshwater lens currently available do not representatively cover the whole model area and thus there is a need to study this topic further.

Structures such as conduits, faults and other zones of higher permeability in the aquifer have been found to potentially have a significant influence on the spatial extent of the catchment which contributes with water to Sian Ka'an. It is however important to obtain more knowledge about the location and nature of the large-scale regional structures, and it has been shown how such information can be included in a hydrological model of the area to quantify flow of water and transport of pollution.

Hydrological models, such as a local-scale conduit-matrix model, and a regional-scale equivalent porous medium model, can be used to delimit the groundwater catchment of the Sian Ka'an Biosphere Reserve and analyze flow patterns. In a management perspective it is important to know which areas that contribute with water – and possibly also with groundwater pollution – to other areas, and also to obtain knowledge as to how fast pollution is actually transported and spread in the system. For instance, it was clearly demonstrated by the simple conduit-matrix model that there can be an immense difference in groundwater flow velocities in a conduit compared to in the matrix. This is also why it is important to take conduit flow explicitly into account when considering pollution transport in the aquifer and water management of the area in general.

Visualizing groundwater catchments and the transport of pollution can be a great advantage with respect to communication of results, and it has in the present project been shown that the hydrological models used here can be useful for this purpose. A hydrological model can thus be an important tool for showing the set of problems at hand to the policy- and decision-makers as well as to other stakeholders. Furthermore, a visualization of the potential problems can assist in putting issues regarding groundwater protection and management on the agenda.

At the same time it has however also been revealed through the project work that there is a great need for further data in order to calibrate the hydrological models properly and to improve the description and understanding of the system.

### 10.2 Perspectives for Application of the Results in Actual Water Management

There are different strategies and tools available for sustainable water management. Below we will first present tools that can be directly linked to outputs from hydrological modelling, and subsequently, tools with a more indirect relation to this is briefly discussed

In Europe and the United States an approach to groundwater management of karstic aquifers is vulnerability mapping where the geological sensitivity of the medium to pollution is characterized and documented throughout the location (e.g. Davis *et al.*, 2002; Andreo *et al.*, 2006). In Europe, the newest approach in addition entails hazard mapping, which involves mapping the sources of pollution in the catchment and classifying the types of pollutants (Andreo *et al.*, 2006). An assessment of the risk for contamination is then made based on an overlay of the two maps, and management decisions can be based on this outcome. However, this approach is currently applied to well-fields, i.e. on a relatively smaller scale, rather than large areas such as a Biosphere Reserve. However the method seems to have potential for also application for a larger area.

The type of results presented in the present project provides an advanced way of mapping vulnerable areas, since physical data is used for determining the actual groundwater flow patterns. The results generated from the groundwater model, e.g. catchment zones and traveling times, can be directly applied in a management perspective. We have especially in this report focused on the Sian Ka'an Biosphere Reserve, but the results can also be related directly to the caves and the coral reef as ecosystems on their own of particular conservation interest.

A management tool which is straightforwardly related to such results from the model is the delineation of groundwater protection zones. Groundwater protection zones are areas where human activities with potential for groundwater pollution are strongly regulated so as to preserve the subsurface water resource. Their spatial extent is based groundwater divides or on traveling times from potential sources of pollution. An important example is the suggestion of Escolero *et al.* (2000) to establish a hydrogeological reserve for Merida, in order to ensure sufficient drinking water resources for the town. Merida is the largest city on the peninsula with 600,000 inhabitants and the need for groundwater protection is urgent as the upper third (~15 m) of the thin freshwater lens under the city has been found unfit for human consumption (Marín *et al.*, 2000). This also illustrates how important it is to prevent contamination of the aquifer at the Caribbean coast in due time, and the perspectives if nothing is done.

Also elsewhere in the world groundwater protection zones are established based on the travel time of the particularly critical pollutants for a specific site, e.g. based on the travel time it takes for pathogens to die, or for a nitrate load to be reduced to below a certain threshold (e.g. Veselic, 2003). The traveling times output from the hydrological models may aid in determining such zones.

Another tool for management of the area, for which hydrological models may be useful, is for multiobjective optimization of land-use patterns. As the name implies, multi-objective optimization methods not only consider the environmental objectives of land use, but also e.g. economic and social objectives. Based on specification of the wanted management objectives the method numerically optimizes the spatial land use pattern. This is thus a tool with potential for both assisting the management of water resources as well as economic and social development. Tampieri (2006) showed the potential for this method to be used for the Tulum development plan area, but also showed that this tool needs significant further development, and it is thus an area of active research.

Other tools for groundwater management are not necessarily explicitly linked with the output from a hydrological model but are more generally related to having an increased hydrological understanding of the system. These tools are regulation and monitoring. Regulation of water abstraction must be carried out to ensure that the groundwater resource is not exploited beyond the carrying capacity. However, this can only be done when the magnitude of the groundwater resource and the replenishment is adequately quantified. In this connection it is also important to investigate the vulnerability of the groundwater resource with respect to saltwater intrusion from the coast, or saltwater upconing from the underlying saline water, in case of excessive pumping. The latter could, when the necessary data is obtained, be investigated through scenarios run with an expanded hydrological model which takes both saltwater and freshwater flow into account.

Regulation is also essential with respect to wastewater management, since it is common practice in the model area to dispose of both municipal and industrial wastewater directly to the aquifer - often untreated (Marín, 2005). When wastewater is directly discharged into a cenote it is obvious that there is a pollution problem. In addition, the common practice of injecting wastewater tens of meters below the halocline into the saline part of the aquifer has been shown to cause the lighter wastewater to rise upwards and end up in the freshwater part of the aquifer. Conduits can then transport and spread the pollution rapidly, and tidal effects may also cause both a flow of the pollution towards inland well-fields or towards the coastal lagoons and coral reef, as discussed by Beddows *et al.* (2005). By using a hydrological model to delineate catchment zones and areas of particular groundwater protection, it will be possible to delineate areas where a particular effort should be made to regulate wastewater, as well as ensuring that it is not disposed of in priority areas. Beddows *et al.* (2005) in addition suggest that injection wells should be abolished all over the Yucatan aquifer, since the aquifer medium here is so extremely vulnerable, and this is also a regulatory issue.

Monitoring is another useful water management tool because it can document the state of affairs and indicate to decision-makers if a problem is getting out of hand or if the management measures applied do not yield the wanted result. Delineated protection zones and the target areas of conservation would especially be places where initiation of monitoring could be useful as a supplement to other water management tools.

Finally, it must be noted that a prime aspect for groundwater management in karst areas to succeed is that awareness on the potential problems and their prevention and management are ensured. As documented by Ekmekci & Gunay (1997) a karst water management scheme is dependent on the consciousness of the local authorities. This is in part strongly related to that the findings of technical reports, such as the present one, are explained in non-technical terms to the local authorities (Ekmekci & Gunay, 1997). Already now, Amigos de Sian Ka'an are working in this field and lobbying activities with the purpose to raise awareness on the level of decision-makers are being carried out. The visual nature of many of the outputs from the hydrological models may be a useful tool for ensuring that the results of hydrological studies are spread wider than just within scientific circles.

## 11 Conclusion

The water resource dynamics in the catchment that encompasses the Sian Ka'an Biosphere Reserve have been modelled with a simple 1D analytical hydrological model and with spatially distributed 2D hydrological models. At present the quality of the input data to the models only show a relatively small improvement in model fit for these two types of models, with a MSE of 2.76 and 2.11, respectively, in favour of the 2D model. The shape of the halocline inland may be modelled well with a 1D analytical model, whereas this is not the case in areas with extensive conduit development, as also found by Beddows (2004). Thus, the 1D model has limited value in such locations. The 1D analytical modelling has also showed that the Ghyben-Herzberg relationship is not necessarily valid in the model area since the model seems to need different parameter values when fitting to halocline and water table data, respectively. The ratio between the height of the water table and the depth to the halocline is thus not 1:40, but is around 1:15 for the data used in the present project. The data on the vertical extent of the freshwater lens currently available do not representatively cover the model area and are of low quality, and thus there is a need to study this topic further.

A 2D model can take the spatial variation of hydrogeological conditions in the model area into account, and compared to the 1D model also yields many more types of model outputs, which can be used directly in water management issues. Only this type of model can show the flow patterns of the catchment, which is necessary in the context of this project.

2D conduit-matrix models are particularly advantageous on a local scale, since these give a more correct description of the turbulent and often rapid conduit flow which dominates the karst aquifer. It has been shown that the coupling between the MIKE SHE and MOUSE software is suitable for simulating such karst flow problems. However, at the current stage, more data on the conduit systems, such as extent, dimensions and flows are needed in order to develop and calibrate useful conduit-matrix models of the area. Tests with simple EPM models with high permeability zones have shown that these types of models can more or less yield the same results as a conduit-matrix model, and because they are more computationally efficient, they can therefore be useful for developing a regional-scale model of the study area.

Conduits and other zones of high permeability *must* be taken into account when developing models of the Sian Ka'an catchment, because they can have a significant influence on the groundwater flow patterns and the extent of the catchment. Visual inspection of satellite imagery can be used to identify some of these large-scale structures, and with geophysical investigations it has been confirmed that at least some of these structures are indeed zones of higher permeability. By supplementing with information from literature and on cenote locations, zones of potential high permeability in the model area have been delineated, and these have been incorporated into the regional-scale hydrological models. Various model scenarios have been developed that include some or all of the identified structures. The quality of the present calibration data does not show a significant difference between these scenarios and none of the identified structures can therefore be ruled out at the present stage.

The 2D hydrological models can be used to aid the protection of the wetland water resources from contamination by delineating the catchment that contributes with water to these areas and by showing how potential groundwater pollution may spread. However, additional input data is needed in order for

the model to adequately simulate the actual conditions, and thereby be relevant as a tool in water management. This includes quantification of evapotranspiration rates, collection high quality water level data for calibration and validation of the model and also investigation of the extent and nature of the potential high permeability zones.

The results from the preliminary regional-scale hydrological model developed in this project show that it cannot be excluded that the area covered by the urban development plan for Tulum contributes with water to the Sian Ka'an Biosphere Reserve, even when not taking into account the possibility of a direct conduit connection between these two areas. This finding may be critical in relation to the proposed development of the Tulum area, and therefore, in order to investigate this hydrological link further, the nature and southern extent of the possible low permeability zone at the coast near Tulum must be investigated along with a further exploration of the possibility of a direct conduit connection.

The outputs of the regional-scale hydrological model also show that Sian Ka'an is fed by groundwater which originates from the area around the large town of Felipe Carrillo Puerto and which may reach the reserve in less than 10 years. In addition, groundwater contribution to Sian Ka'an is likely to also come from the agricultural area around Andres Quintana Roo. If the identified potential high permeability zones do in fact have a high hydraulic conductivity in the model area, this may also mean that Sian Ka'an receives water from the agricultural areas in the southern central part of the model area. Through the high permeability zones the model has visualized how pollution may potentially spread over larger areas and may reach Sian Ka'an. The advancement of the hydrological understanding of the area which may be derived from an improved hydrological model may be used to establish groundwater protection zones in a step to manage the groundwater resources of the area.

# 12 Directions for Future Research

The work presented in the present thesis has lead to the development of a first regional hydrological model of the area of study. Although the data available has not allowed for it to be fully representative, it is considered to be an important first step in understanding the hydrology on a regional scale.

Following this, the work presented here has also highlighted knowledge gaps which may point to the directions for future research. These are presented below.

#### 12.1 Data Needs

The current data quality does not allow for a proper calibration of the model. Ground surface levelling of water table measurement locations in the entire model area is therefore needed for more accurate determination of freshwater heads and a better calibration of the hydrological model. In addition, the potential for acquiring water level data by remote sensing should also be explored. Obtaining flow data from conduits and coastal discharge measurements would also be advantageous to calibrate the model against.

Data for the location of the halocline found in the literature as well as the data produced during the field investigations have been measured in an area with high permeability due to the presence of conduits. The high permeability may cause a thinning of the freshwater lens and it is therefore questionable whether the current data for the shape of the halocline is representative for the entire model area and e.g. more ProTEM measurements along with more accurate water table elevation data are needed throughout the model area for a more accurate characterization of the vertical extent of the aquifer.

The large high permeability structures identified from interpretation of satellite imagery have shown to potentially have a large impact on the size of the catchment supplying water to the wetlands of Sian Ka'an. Therefore, there is a need to further investigate these structures and whether they are actually associated with significant water flow and if so, the size of this flow and how deep the structures extend into the subsurface. Also the presence of conduits between the area covered by the development plan for Tulum and Sian Ka'an should be explored e.g. by airborne and ground-based geophysical surveys and further scuba dive explorations. Furthermore, the possible low permeability zone at the coast near Tulum needs to be investigated further, especially with respect to the southern extent of this zone and its hydraulic conductivity.

Current estimates of recharge span from 15% to 60% of mean annual precipitation and are thus very inaccurate. This hinders a reliable estimation of a water balance for the catchment. Efforts to more accurately determine evapotranspiration and thus also recharge should therefore be made. In the pre-thesis project remote sensing data analysis methods such as the S-SEBI or SEBAL methods were suggested to be appropriate for this purpose.

Another issue that should be further explored is the ability of trees with tap roots to reach the water table and thereby tap water from the saturated zone. Also water uptake and evapotranspiration potential for vegetation in the wetlands should be further investigated, as this will allow for a more detailed spatial discrimination of evapotranspiration.

## 12.2 Modelling Efforts

So far, the effect of the wet and dry season has not been determined for the regional hydrological model. This should therefore be further investigated and in that regard it could also be relevant to include the unsaturated zone in the model as infiltration times may be important and since significant storage may take place here.

A potential threat to the water resources in Sian Ka'an is the urban development plan for Tulum proposed by the Municipality of Solidaridad. Therefore it is extremely important to further investigate the hydraulic connection between the area covered by the development plan and Sian Ka'an. In this regard the Ox Bel Ha system which is located in between these two areas is key, as there is a possibility for a direct connection from Ox Bel Ha into the Reserve. A detailed conduit matrix model should therefore be set up for this area. This model should be transient and include the tidal effect and explicitly model large outflows. Also the effect of the amount of water abstraction and pollution loads as expected as a consequence of the development plan should be included.

Another threat to the water resources of Sian Ka'an is the urban and agricultural areas Felipe Carrillo Puerto and Andres Quintana Roo. The effect from these areas should be further investigated by the regional model, namely the effect of water abstraction as well as household, industrial and agricultural pollution loads from these areas.

#### 12.3 Management Issues

The concept of groundwater protection zones should be further developed when more knowledge of the catchment has been obtained. This could involve risk mapping and should also involve identification of critical pollutants and their fate in a karstic aquifer. Identification of appropriate monitoring sites could also be relevant.

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