1. INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

Karst is the term used to designate the geologic formations constituted by sedimentary rocks, especially carbonate rocks, where the water action has created great conduits and underground caves (Custodio & Llamas, 1983). Between 7% and 12% of the continental surface of the Earth corresponds to karst terrains (Drew, 1999, cited in Escolero *et al*., 2002). Examples of these formations are observed, for instance, in the western USA, the Mediterranean coast or the Indonesian islands. The karsts have an increasing interest since more than 25% of the world's population depends on water contained in these systems (KWI, 2008).

Carbonate rocks are characterized by their high solubility in water. To tackle properly the dissolution of calcite it is necessary to invoke several species and a number of chemical equilibrium equations, but for moderate pH values the system can be simplified so that, dissolution of calcite occurs if there is CO_2 dissolved in the water according to the following equilibrium reaction:

$$2H_2O + CaCO_3 + CO_2 \Leftrightarrow H_2O + Ca^{2+} + 2HCO_3^-$$

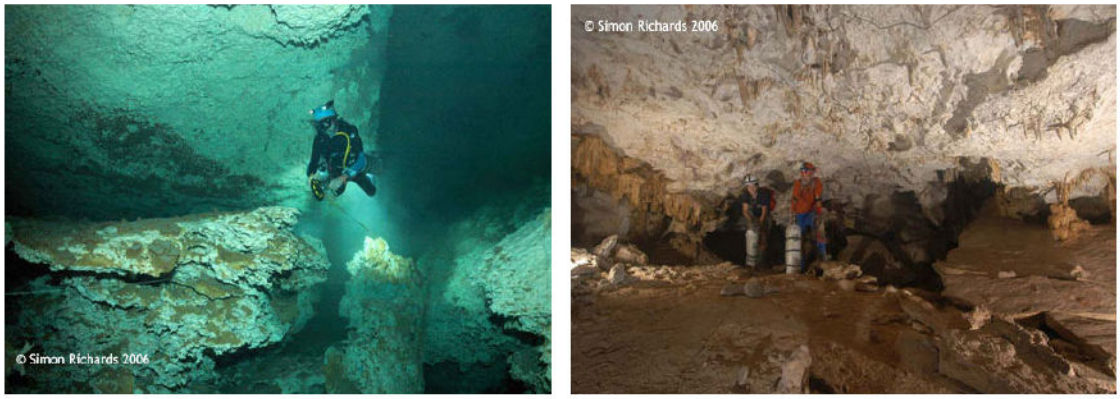
Since the concentration of dissolved CO_2 depends on temperature and atmosphere pressure, the climate conditions are a determinant factor in the dissolution processes (Bakalowicz, 2005). Dissolution becomes a geological factor able to shape the outcrops, giving spectacular relief forms (Figure 1.1).

Figure 1.1. Small streams in the surface of carbonate rocks (Majorca Island, Mediterranean Sea).

During the late geologic time, CO_2 was only produced in the subsurface by biological and geological processes (Bakalowicz, 2005). Thus, the main dissolution of carbonate rocks was produced by groundwater. That conferred a high porosity to these rocks and, in some cases it even caused the formation of the sinkholes and caverns characteristics of karst (Fetter, 2001). In this kind of geology the groundwater can flow in the matrix, the fractures and the caves.

Although the development degree of the karstic caverns is variable, some common features have been observed in many karstic systems. Indeed, usually there is a scarcity of both groundwater supplies and surface water bodies. This is due to the high permeability of the karst terrains, which produces the leakage of the water through the rock and prevents the formation of surface reservoirs (Ekmekçi & Günay, 1997; Escolero *et al.*, 2002). Other problems are related to the karst geology. The sinkholes formed by the dissolution of the rock can collapse, causing unpredictable damages. Nevertheless, the most extent problem is the fast transmission of pollution through the karst. This pollution can be due to hydrogeologic factors, anthropogenic influences or sources of contamination in the area (Aller *et al*, 1987, cited in Davis *et al.*, 2002). In the case of the karstic aquifers placed in the coast, a new problem is added: the salinity penetration. Indeed, the heterogeneities of these aquifers tend to spread the mixing zone in a larger zone than in the homogeneous aquifers (Wicks & Herman, 1995). It has to be taken into consideration when the location of wells for freshwater supply is decided. Moreover, the karstic coastal systems have to face also the expected growth of tourism and, in many cases, a high population density. Thus, in these aquifers, there is a large demand of water and pollutant generation.

This thesis deals with the coastal karstic aquifer located at the Caribbean coast of the Yucatan Peninsula, in the state of Quintana Roo, Mexico. This area is characterized by high developed cave systems. The dimensions of many of these caves allow the speleologists exploring both dry and flooded caves (Figure 1.2). At present, the limit of these caves has been estimated in 8-12 km inland (Smart *et al.*, 2006).



a) b)

Figure 1.2. Flooded cave (a) and dry cave (b) explored by the speleologists in the Yucatan Peninsula, Mexico (Richards, 2008).

A thin freshwater lens flows through these systems on top of saline water that penetrates from the sea. Its thickness has been estimated in less than 50 m (Escolero *et al.*, 2000). Its importance arises from the fact that the fragile aquifer is the only source of freshwater in the region (Alcocer *et al.*, 1998; Doehring & Butler, 1974). Furthermore, the scarcity of water is a determinant factor in the Yucatan Peninsula, despite the fact that the rainfall is very significant. Sometimes it can reach 1500 mm/year, but 85% of this precipitation is returned to the atmosphere by evapotranspiration and the extremely permeable carbonate rocks causes the infiltration of the remaining portion of rainfall (Alcocer *et al.*, 1998), with negligible runoff.

The aquifer has been able to supply Yucatan's inhabitants historically. The ancient Mayas already took the water from the cenotes (Figure 1.3), which are water bodies contained in limestone cavities that are very common in the Yucatan Peninsula (Alcocer *et al*., 1998).

a) b)

Figure 1.3. Images of two different cenotes taken from the air (a) and from the ground (b).

Nowadays the aquifer is subject to a high environmental stress, due to the population growth in this area experimented during the last decades of the 20th century. Different factors have contributed to this phenomenon. The implementation of health programs caused a decrease of the death rate. Apart from this, due to the high population density of other zones of Mexico, the government has stimulated the colonization of the Yucatan Peninsula. Moreover, it is worthy considering the tourism that is becoming an important economical source (Doehring & Butler, 1974). All of that derives in a need of large amounts of freshwater supply.

Studies on the Yucatan Peninsula reveal that the most contaminated areas of the aquifer coincide with the most urbanized zones (Graniel *et al*., 1999). These contaminants are supposed to flow towards the coast but if the hydraulic gradients are reversed by an excess of pumping they can move towards the abstraction wells (Steinich & Marín, 1997). Moreover, as in many coastal regions, it is a common practice to inject the waste water into the aquifer by means of coastal wells, far away from the recharge areas (Davis *et al*., 2002). In systems with low permeability it does not imply risks because diffusive flow takes place and, therefore, the contaminants transport is slow. Furthermore, the contaminants can be degraded due to different processes that occur into the terrain. But in aquifers with high permeability, where the advective flow is dominant, the contaminants move rapidly (Beddows *et al*., 2005). They can be transported inland, towards the freshwater abstraction wells, or towards the coast, with an impact on the quality of the freshwater supplies or the bath water in the beaches.

Another factor that has to be considered is the Sian Ka'an Biosphere Reserve, located at the south of the area studied in this project. This natural reserve has been

identified as World Heritage site by UNESCO (Neuman & Rahbek, 2006). But due to the high transmissivity of the karst systems, the actions that take place in the area have an important repercussion on the reserve.

Since groundwater may be a limiting factor of the economy and development in the Yucatan Peninsula, it has to be protected in quantity and quality. That implies protection measures as well as prevention and intervention measures (Veselic, 2003). The protection of groundwater has not only an environmental interest but also it is cost-effective, since the prevention is cheaper than the remediation measures (Davis *et al*., 2002). In order to protect the resources of the coastal karstic aquifer, different strategies can be carried out. Some authors point out aquifer monitoring network (Doehring & Butler, 1974), zoning of land use and code of practice (Escolero *et al*., 2002) and consciousness of the population (Ekmekçi & Günay, 1997).

In the present study, a numerical modeling of groundwater flow and salt transport in karstic system is conducted. This study focuses on the effect that the presence of the conduits has on the saline intrusion compared to the widely known distribution in non karstic aquifers. This research will, therefore, represent a challenging opportunity to obtain a better understanding of the Yucatan karstic system in order to develop sustainable drinkable water and waste disposal strategies.

1.2. OBJECTIVES

The overall objective of this master thesis is to characterize coupled fluid flow and salt transport in a simplified karstic system consisting on a porous matrix crossed by one conduit. With this aim a model is developed using a Finite Element Method (FEM) code. A first step towards achieving the established objective is to study groundwater flow in the karstic system without considering salt transport. Thus, it is possible to assess the effect of the conduit on the flow distribution. For this purpose two models, in two and three dimensions are created. Next, the variable density problem is faced. In front of the great complication that the whole problem entails, initially the problem is studied in two dimensions and without taking into account the conduit. The following step is to include the conduit in a two-dimensional model. Finally, the problem is extended to three dimensions. Since the estimation of some parameters is not really accurate, a sensitivity analysis has been carried out.

In the following chapters, first a literature review is presented concerning the approaches that have been used in the modeling of karstic systems (Chapter 2). That is followed by a description of the main features of the model area (Chapter 3). Next, the methodology used for this research is explained in detail, including the conceptual model, the theoretical background, the parameter estimation and the modeling approach (Chapter 4). The results and discussion are presented next (Chapter 5), divided into two main topics, the groundwater flow model and the variable density flow model. Finally conclusions are drawn (Chapter 6).