2. LITERATURE REVIEW

In the past several decades, a great number of researchers have invested their efforts in studying the behavior of karstic systems (e.g., Custodio & Llamas, 1983). This is a consequence of the interest in the water resources in karstic systems as well as in the problems related with this particular geology, mentioned in section 1, such as the collapse of sinkholes and the fast transmission of pollution. Nevertheless, the modeling examples of karstic aquifers located at the coast are very rare (Arfib & Marsily, 2004). The extreme heterogeneity of these systems complicates its study. Indeed, the methods used classically in hydrogeology (i.e., borehole, pumping test and distributed models) cannot be applied in karstic aquifers since they can only be extended to some parts of the aquifer (Bakalowicz, 2005). Thus, the main problem of the karstic aquifers modeling, specifically the coastal karstic aquifers, is the great simplification that is necessary to make (Groves *et al.*, 1999, cited in Arfib & Marsily, 2004). A generalized conceptual model for karstic aquifers developed by White (2003) show the main components of these flow systems. As shown in Figure 2.1, the recharge into these aquifers comes from the surface water that penetrates into the aquifer by means of sinking streams, the internal runoff, the diffuse infiltration and the recharge from perched catchments. Since this conceptual model is general, the discharge is carried out only through the springs. In the case of coastal karstic aquifers, most of the groundwater is discharged to the sea.

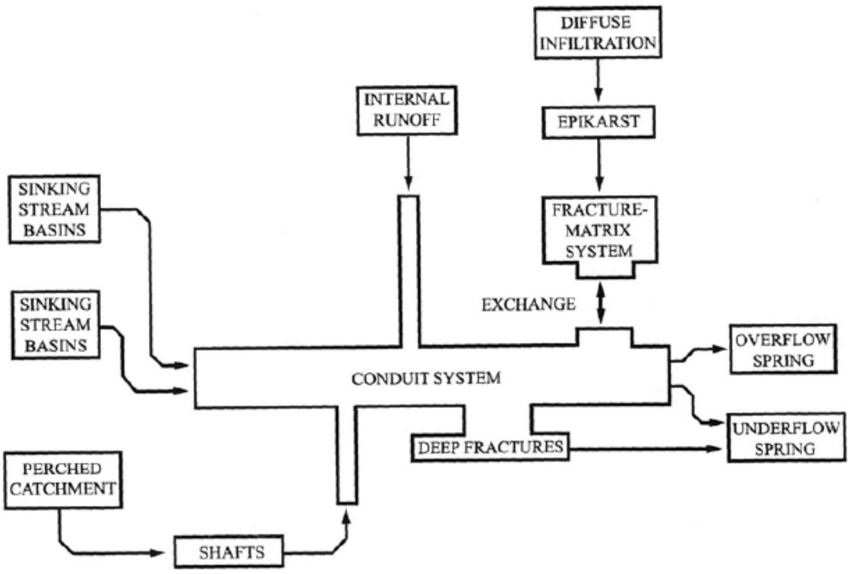

Figure 2.1. Conceptual model for a karstic aquifer (White, 2003).

Not all the components exposed in Figure 2.1 appear in all aquifers. Depending on the degree of karstification some components become more important than others. The degree of karstification can be determined by the porosity of the system. According to Worthington (2003), the karst systems have three porosity elements. These elements are sketched in Figure 2.2 and are described as follows:

- One-dimensional or linear elements called channels. When turbulent flow takes place in them, they are usually termed conduits. If people can access into them, they are known as caves.
- Two-dimensional or planar elements, such as joints and faults.

- Three-dimensional matrix.

The channels are characterized by low storage and high velocities while the matrix and the fissure system have a higher storage and low flow velocities (Worthington, 2003).

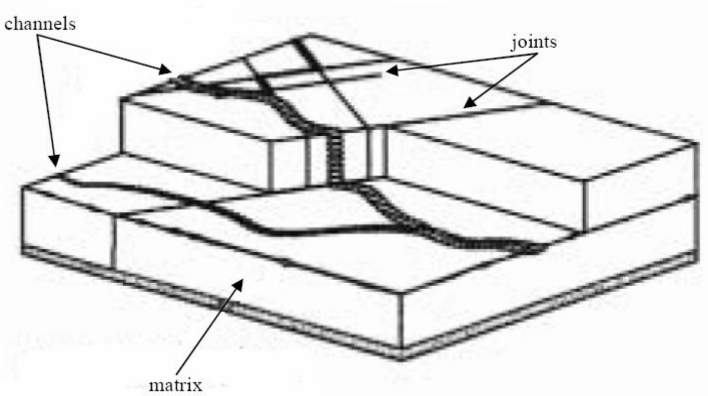

Figure 2.2. The three porosity elements that can be present in a karstic aquifer (Worthington, 2003).

The existing models of coastal karstic aquifers are very similar to the ones developed for continental karsts (Arfib & Marsily, 2004). The quantitative modeling of continental karstic aquifers can be classified into three approaches: lumped parameter models, analytical models and numerical models (Cheng & Chen, 2005). The lumped parameter models include the black-box models and the water-box models. In the first type, the model is considered as an independent box reservoir while, in the second one, the aquifer is divided into several box reservoirs assembled by pipes. Thus, in both cases it is possible to represent the response of the system to an input signal, without considering all the processes that occur into the aquifer. This methodology is very similar to the one used in surface hydrology (Bakalowicz, 2005). Indeed, lumped parameter models are used to study the relationship between the rainfall and the discharge. This is the case of the parsimonious model developed by Barrett & Chaberneau (1997), sketched in Figure 2.3. The reservoirs correspond to the different watersheds that exist in the recharge zone. Each reservoir is characterized by the water level and the area. It is worth considering that this kind of models, even with a low level of complexity, can provide good results (Perrin *et al.*, 2001). However, they are not very relevant to this project because they cannot represent the density driven flow that happens in the coastal karstic aquifers.

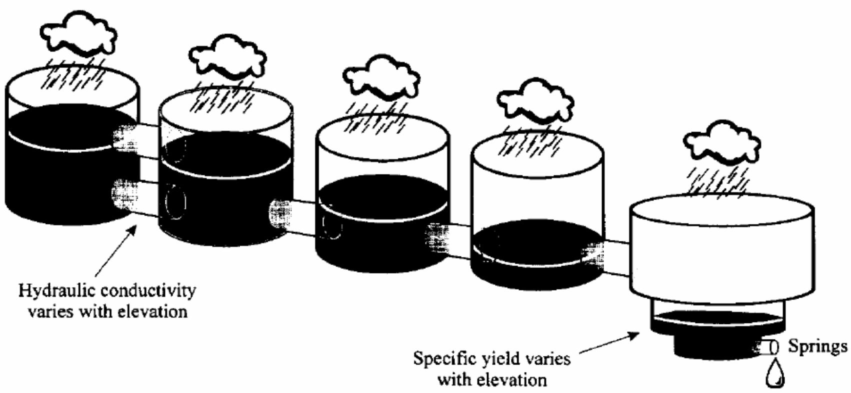

Figure 2.3. Schematic diagram of the lumped model created by Barrett & Chaberneau (1997)

The second approach that is usually applied to continental karsts, i.e. analytical models, cannot be used in coastal karst aquifers either. These models can be applied only for a few boundary conditions. Under variable density, the problem becomes very hard to deal analytically, since the salt transport equations are highly nonlinear and coupled. Thus, the equations must be treated iteratively (Herbert *et al.*, 1988).

After the considerations exposed above, numerical models are the only tool used in continental karsts that can also be applied to coastal karsts. The numerical models that have been developed for karstic systems can be divided into four broad categories depending on the simplifications made:

1. The karstic system is considered as an equivalent porous medium. The channels and fractures can be implemented as high permeability zones (Arfib & Marsily, 2004). This represents the case of a dominant flow through the matrix. A schematic representation of this kind of models is shown in Figure 2.4.

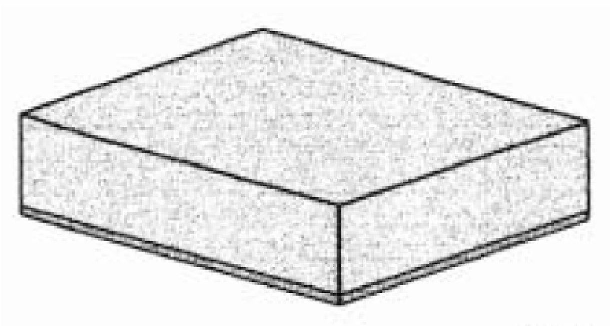

Figure 2.4. Equivalent porous medium model (Worthington, 2003).

Some authors (e.g. Scanlon *et al.*, 2003; Larocque *et al.*, 1999) have concluded that this kind of models is able to simulate the flow in highly karstified aquifers. In fact, some authors have used this approach to model the aquifer in the area of Merida (in the northwestern part of the Yucatan Peninsula) and obtained satisfactory results (González-Herrera *et al.*, 2002). Nevertheless, in the literature some detractors point out that it is an unrealistic approach (Arfib & Marsily, 2004).

2. The karstic system is reduced to a network of caves which, previously, has been individually identified. It allows studying the behavior of the cave systems in front of a storm input (Halihan & Wicks, 1998). The cave is modeled as a close conduit where pipe flow occurs. The actual geometry of the cave is simplified to ideal shapes (Figure 2.5). The determination of the cave features is very important since the model shows a high sensitivity to some parameters, such as the length, the width and the Manning's roughness (Peterson & Wicks, 2006).

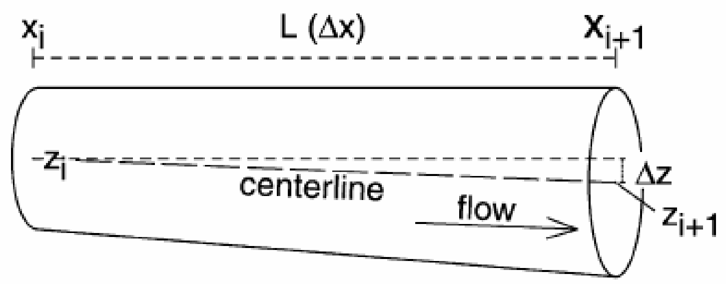

Figure 2.5. Schematic diagram of an ideal cave passage (Springer, 2004).

Although this model is applicable to some karstic aquifers, it should not be considered as a universal solution (Peterson & Wicks, 2006; Springer, 2004). Apart from this, the main disadvantage is that the interaction between the caves and the matrix is not taken into account. Therefore, it cannot be used for modeling saline intrusion although it could simulate a localized entrance of saltwater (Arfib & Marsily, 2004).

3. In the third category, the medium is modeled as a discrete network of fractures with high permeability that overlaps to a low permeability matrix. Between both features there is a hydraulic interaction (Cheng & Chen, 2005). In Figure 2.6 an example of this model is exposed.

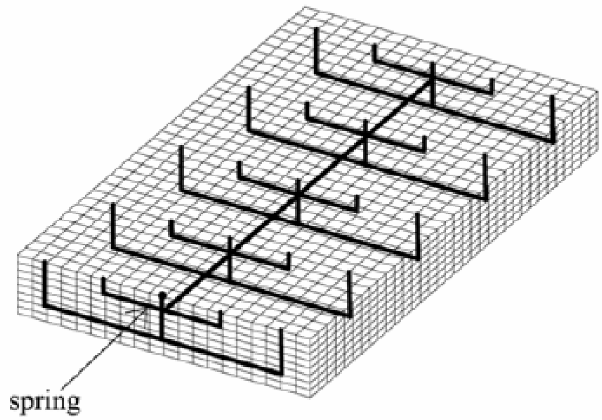

Figure 2.6. Fracture network-matrix model (Cornaton & Perrochet, 2002).

The results provided by this kind of models show the definitive influence of the karstic network density in the hydraulic responses of the system (Cornaton & Perrochet, 2002). This approach allows simulating the heterogeneity of flow distribution observed in karstic systems (Gylling *et al*., 1999). Nevertheless, it requires a precise knowledge of the fracture network. Due to the difficulty of getting this information, this model is not broadly used.

4. The model combines a conduit network with a fissured matrix. The latter is considered as an equivalent porous medium where Darcian flow takes place. In the conduit, turbulent flow is implemented (Arfib & Marsily, 2004).

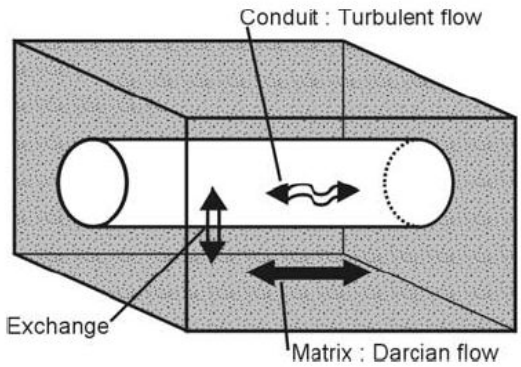

Figure 2.7. Sketch of conduit network-matrix model (Arfib & Marsily, 2004).

The main advantage of this method is that it considers the exchange that occurs between the network of conduits and the surrounding matrix (Figure 2.7). Indeed, when the conduit is flooded, water and solute penetrate from the conduit into the matrix. When the conduit empties, water and solute return slowly from the matrix into the conduit. However, the mobility in the matrix of both water and solute is very small. Once the fluid and solute enter into the conduit, they stay there until they are discharged out (Peterson & Wicks, 2005).

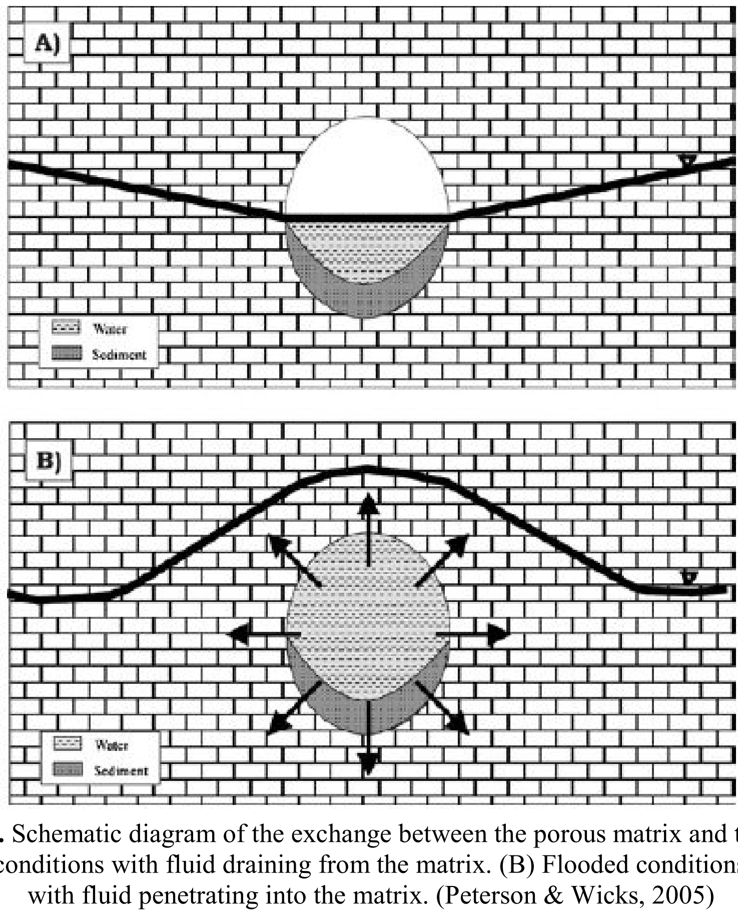

Figure 2.8. Schematic diagram of the exchange between the porous matrix and the conduit. (A) Baseflow conditions with fluid draining from the matrix. (B) Flooded conditions in the conduit with fluid penetrating into the matrix. (Peterson & Wicks, 2005)

This is the approach that has been chosen in this project to model the coastal karstic aquifer located at the northeastern part of the Yucatan Peninsula. Although this method has not been applied to coastal aquifers, it has already been applied to simulate solute transport (Arfib & Marsily, 2004).