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Karst and Waters in it –
A Literature Study on Karst in General and on Problems and Possibilities of Water Management in Karst in Particular

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Summary

Water is, and will in the near future be even more, a key issue for the global development, and for issues concerning equal rigts for all mankind. Water is a necessity and a scarce resource in great parts of the world and it therefore exists a great need for development and management of the world's waters. With fresh waters being increasingly accentuated for their importance in global development and sustainability the goal of development of knowledge, understanding and actual management of the world's waters needs to be reached as soon as possible.

Areas of karst worldwide are known for their scarcity of water and their high vulnerability to environmental impacts. Karst are landscapes formed through the assistance of water in soluble rocks, such as i.e. limestones and dolomites. Karstic landscapes are present in large parts of the world, but most importantly these areas are often also densely populated. Approximately twenty-five per cent of the world's total population either live in or get their drinking water from aquifers in karstic landscapes and this makes karst landscapes interesting and important areas to study and develop the understanding for management of water resources.

Proper management of karst waters requires monitoring and information intake of the state and functionality of the aquifer. This undertaking can only be achieved if karst, and all properties of it are understood and combined with knowledge from the field of hydrology.

Since the difference of karstic rocks in relation to other soil/rocks in/on which water moves hasn't been fully appreciated in the past, these areas have been unsufficiently managed and problems have been evident. Often occuring problems in karst areas are; waste-disposal leakage that contaminates available fresh-water; water scarcity and irregular occurrence of water and difficulties with locating fresh-waters. Strategies of water management often used in other terrains also work less efficiently in karst. One such example are dams, which have been shown to have a substantial leakage problem in karst.

Although there are many management problems concerning the permeability of karst aquifers, some characteristics of karst aquifers also facilitates management and monitoring.

Abstract

Karst are landscapes and features of hydrological and geological importance developed through weathering of water in mostly carbonate rock terrains. This paper maps out karst areas of the world, describes the properties of karst and karst hydrology and aims to define problems and possibilities of water management in karst landscapes. Karst aquifers differ in many aspects from other aquifers with water movements in regular being faster, more turbulent and irregular in occurrence and are amongst other things often characterised by a deficit in water supplies and by difficulties of predicting the same. Proper management and actions through better understanding of karst aquifers can minimize environmental problems specific for karst and maximize the use of possibilities that karst aquifers possess.

Keywords Geography · Physical Geography · Karst · Karst Hydrology · Hydrology · Karst aquifer · Ground water · Water management

Abstract

Karst är landskap och karakteristika som är viktiga både ur hydrologisk och geologisk synpunkt och som är utvecklade genom vattnets vittring av oftast karbonathaltiga stenar. Denna uppsats kartlägger världens karstområden, beskriver egenskaper av karst och karsthydrologi och strävar efter att definiera problem och möjligheter med vattenhantering i karstlandskap.

Akvifärer i karst skiljer sig i många avseenden från andra akvifärer i att vattenflödet oftast är snabbare, mer turbulent och förekommer oregelbundet. Akvifärer i karst är ofta kännetecknade av bland annat brist på vattentillgångar och svårigheter att förutsäga dem. Lämplig hantering och förståelse av karstakvifärer kan minimera problem som är förknippade med karst och maximera användandet av de möjligheter som karstakvifärer besitter.

Nyckelord Geografi · Naturgeografi · Karst · Karsthydrologi · Hydrologi · Karstakvifär · Grundvatten · Vattenhantering

Contents

Foreword

This paper on Karst Hydrology is a Bachelor Degree Project from the Department of Physical Geography and Ecosystem Analysis at the University of Lund in Sweden. The project is the result of the seminar NGEK01, that is the final part of the Bachelor Program offered by the department. The Bachelor Program corresponds to three years of full-time studies.

The process of writing this paper has been an enlightening and in any case evolving process and to be more or less forced to compile knowledge about the specific subject of Karst Hydrology has been an intriguing and satisfactory task.

I would like to thank my supervisor, prof. Ulf Helldén, for his guidance and Kristoffer Mattisson for reading and commenting on my paper. A thank you to my parents and sisters stands constant.

Lund, 2008.05.30
Veronika Ragúž

1 Introduction

1.1 Background

Water is, and will in the near future be even more, a key issue for the global development. Water is a necessity and a scarce resource in great parts of the world. Therefore there is a great need for development and management of the world's waters – if we want to feed and ensure safe drinking water to people around the world.

Internationally, awareness about the importance of sustainable management of water resources has grown rapidly for some years now and international organisations have been committed to develop the knowledge, understanding and actual management of the waters of the world.

In 2002 The United Nations Environmental Programme (UNEP) presented a report showing the overview state of the world's fresh and marine waters. The report presents the use and management of these waters for the last thirty years and amongst other shows that it is estimated that two-thirds of the world's total population will live in areas that are water-stressed by the year 2025, that twenty percent of the global population lacks access to safe drinking water and that the health of 1,2 billion people is estimated to be affected by water pollution. Further, ground-water has been shown to represent ninety percent of the world's readily available freshwater resources (UNEP 2002).

Water and soil are closely connected and cooperate in nature and thereby affect each other closely and greatly. Different soils affect water differently in ways of travel paths, accumulation rates, the quality of the water and the availability of it. The waters in turn are among the greatest sculptors of the world's landforms and are amongst other things an important factor in the strength of soils. All these - and many other - factors are crucial for mankind and it is therefore important to develop the understanding of the relationship between waters and soils, in order to be able to manage them in a most efficient way.

Physical Geographers, and others, have been studying these relationships for years and much is known about the water - soil and water – rock relationships. In some landscapes this important relationship between water and soil / rock is even more pronounced. Some rocks have been shown to be more soluble and easily sculpted by water than others. These rocks are greatly represented by limestone and dolomite. The type of landscape formed through the assistance of water in such rocks is called *karst*.

Karstic landscapes are present in large parts of the world, and most importantly karst areas are often also densely populated areas of the world. Approximately twenty-five per cent of the world's total population either live in or get their drinking water from aquifers in karstic landscapes (Karst Waters Institute, 2008). This makes karst landscapes interesting and important areas where to study and develop the understanding for management of water resources.

Because karstic landscapes constitute a substantial part of the world's lands, and therefore as well contain, and are a resource of, drinking water for a great part of the world's population there is a need to better understand karst and thereby be able to better manage water in these landscapes.

I would therefore like to better understand karst and karst hydrology. What is karst? Where in the world is karst situated? How does water behave in karst? What are the specific problems of water management in karstic landscapes? How could these possibly be solved? What could be possible specific possibilities of water management in karstic landscapes? Are there any characteristics of karst that could be of special use in future water management?

1.2 Purpose of the Study

The main purpose of this study is to investigate and compile information and knowledge about karst landscapes and their specific properties. This will be done from the specific view of water and water management.

In parts the purpose of the study is; (A) to map out the karst areas of the world, (B) to describe the properties of karst and karst hydrology, and (C) to define problems and possibilities of water management in karst landscapes.

In writing, I have delimited my primary target group as being my fellow students and colleagues as well as other members of the same or adjacent fields of study. With this said, the paper should also be of interest to the layman of some general knowledge and interest in the subject.

2 Method

In order to present and elaborate the subject of karst generally and the subject of karst hydrology in particular a literature study of the subject was performed. This was done by compiling relevant existing published material about Karst and Karst Hydrology.

The production of scientific printed material concerning karst and karst hydrology is numerous and trying to perform a complete compilation of this literature would be of no scientific value, since the compiled material would be as extensive as the gathered material itself (Theorell & Svensson 2007). A *sampling* was therefore performed in order to make a representative selection.

Sampling is a part of the statistical practice where a selection of individuals is used in order to gain knowledge of a particular population (Körner & Wahlgren 2002). In the case of this study the *population* is the complete existing literature on karts hydrology and the *individuals* is the literature that I have chosen to work with in this study. A variety of methods can be employed to choose which individuals that should be a part of the sample (Theorell & Svensson 2007).

The selection of literature used in this study was performed by using the *snowball sampling* method. This statistical method is a sampling method where existing study objects are used to recruit more objects into the sample (Teorell & Svensson 2007). In practice this meant that literature quoted and often occurring in an existing text was investigated further repeatedly, having a starting point in a textbook on general geomorphology that was used as compulsory literature in the geomorphology course that is a part of the Bachelor's program that this paper is a final part of – *Global Geomorphology* by Michael A. Summerfield.

Summerfield's textbook was chosen as starting point since it gives a general description on karst and landforms of it, as well as water movement in karst. For general description of karst and karst hydrology mainly textbooks written on the subject were used. Here, scientists recomended from the part of my supervisor, as well as others often cited in other's work were chosen. At last, for water management issues in karst more recently published articles on the subject were chosen as a complement to the already compiled fundamental description of the subject.

Some deviation from the selection was made when finding articles used for exemplification. These were randomly selected from the total amount of articles available at, or through, the university by use of appropriate keywords.

2.1 Terminology

Karst and the scientific work throughout history concerning karstic landscapes has been followed by a specific inconsistency concerning terminology, which has led to unnecessary difficulties in working and referring to the subject. The common practice among scientists has been to give local names to described phenomena, which in many cases has led to language confusion. Efforts have though been made internationally to agree on a common karst terminology (Helldén, 1974). In that same spirit I will try to use common terms used in the Anglo-American literature when referring to karst and its properties. When needed for clarification synonyms will be used in order to minimise the risk of confusion, and to make reading and understanding of the text easier. The reference used as guideline for terminology in this text is *A Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology* published by the United States Environmental Protection Agency (Field, 2002).

As a rule terms, that could be unknown to the layman, used in this paper will be explained in the running text, but since the primary target group of this study is my colleagues or other faculty members from the same or adjacent fields of study, the definition of some terms may only be found in the glossary at the end of this paper. All terms, which are not explained in the running text, are found and explained in the glossary of this paper. Terms are distinguished by a bolded typeface when appearing for the first time in the text.

3 Results

The term karst, today an international term that comes from the Slovene language via German, is used to describe landscapes and features of hydrological and geological importance developed through weathering of water in mostly limestone terrains. The same features can develop in other soluble rocks such as dolomite, gypsum and sand, but since limestone is the most dominating rock type where these processes occur the literature on karst often consider just limestone terrains when describing karst.

The typical karst landscape is characterised by a bare ground lacking rich vegetation, with a thin or absent soil cover, abundant enclosed depressions at the ground surface and no surface drainage. The landscape however often has well developed underground drainage systems and caves (Summerfield 1991).

3.1 Areas of Karst Worldwide

Karstic landforms can develop in many types of rocks that are readily soluble. Such rocks can be dolomites, gypsum, salt or limestones. Dolomite, gypsum and salt rocks are not as widely distributed as limestones, and therefore, as said before, karst is often connected to areas of pure and massive limestones (Snead, Rodman E. 1980). In Figure 1 a world map of limestone and karst regions is depicted. The grey areas represent major limestone regions of the world, while the blue areas represent major karst areas of the world. Limestone regions have a large distribution over the globe, while karst areas are fewer and do not in fully coincide with the limestone areas. Some regions of limestone rocks don't have developed

MAP 7-3 LIMESTONE AND KARST REGIONS

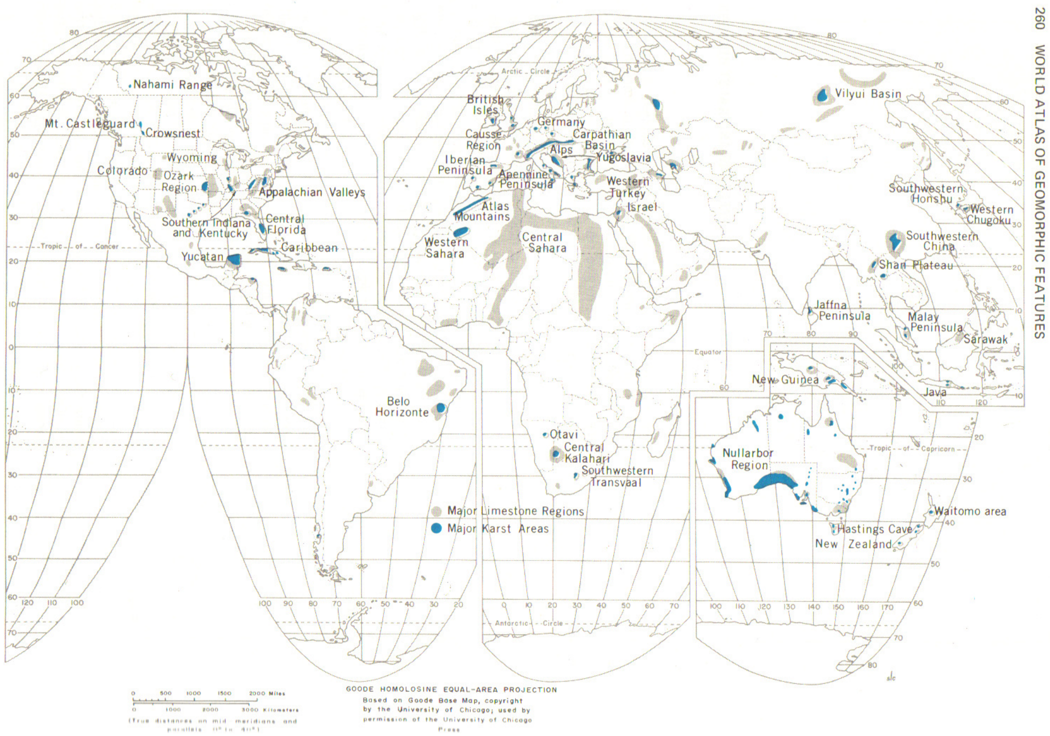

Figure 1. World map of Limestone and Karst Regions (Snead, Rodman E. 1980).

MAP 7-4 CAVES AND CAVERNS OF THE WORLD

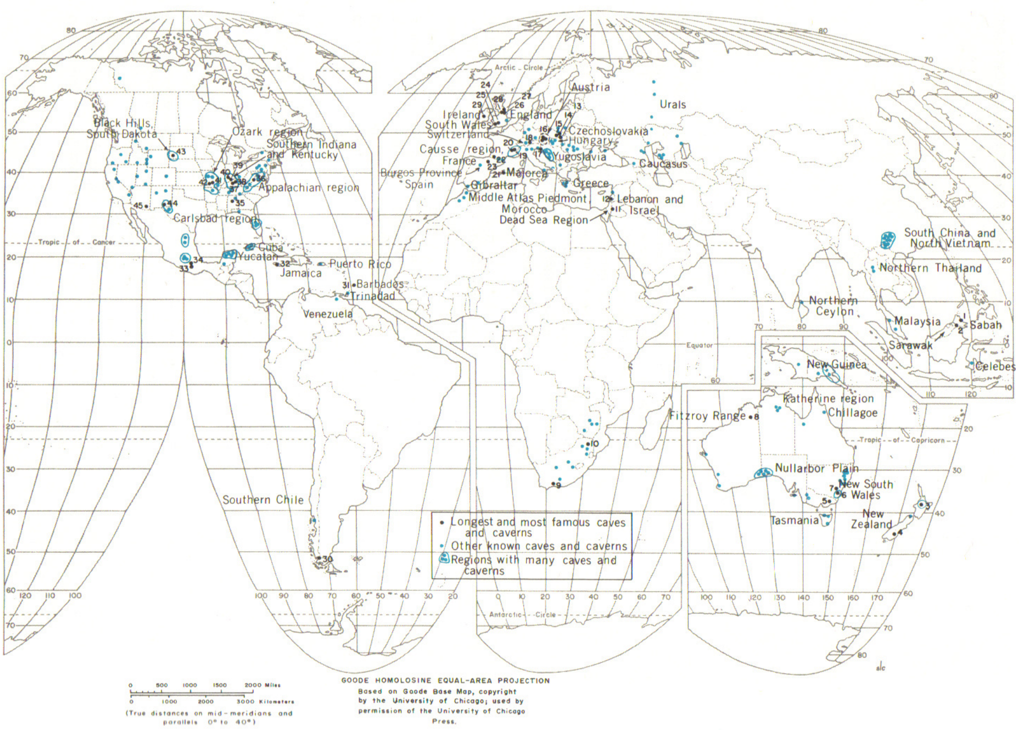

Figure 2. World map of Caves and Caverns (Snead, Rodman E. 1980).

karstic landscapes, and this is probably due to the fact that the limestone permeability in these areas aren't suitable for the formation of karst (Snead, Rodman E. 1980). The properties of rocks and the establishment of karst will be discussed in more detail later in this paper. For now I would like to present the areas of the world that are connected with karst.

In general, the map of limestone and karst regions shows that limestone is widespread over the globe. Parts of the world with less limestone areas are Central Asia and Central South America. A large limestone area also present in Northern Africa and the Arabic Peninsula lack a presence of karst. In other cases karst areas mostly coincide well with the limestone areas.

Figure 2 shows a world map of caves and caverns. The black dots represent the longest and most famous caves and caverns of the world and the blue dots represent other known caves and caverns. Blue dots clustered together and outlined with a blue line represent regions with many caves and caverns. The maps show a correlation between the global distribution of caves and caverns and the karst areas of the world. Caves and caverns are associated with karst areas because underground passages are characteristic features of karst (Snead, 1980). For more about caves see section *3.3.4 Karstic landforms of subsurface drainage*.

The world's best known localities of caves and caverns can be found in Northern and Central America, in Austria and the eastern shore of the Adriatic sea in Europe, in the south east of Asia and in Australia.

3.2 Karst Properties

It is not without difficulties that a division between karst and karst hydrology is made, since the one is largely dependent of the other and thus a description of one will not be whole without an understanding of the other. In this paper I have chosen to first present karst in general before entering the field of karst hydrology, in a motion from the general towards the more specific.

3.2.1 The Formation of Karst

Karst is formed mostly in carbonate rocks with water as its greatest sculptor, developing the landscape's features through weathering, erosion and fluvial transportation of soluble materials downstream. This process of chemical action of water on carbonate rocks causing partial solution of the rock and the erosion and removal of the solutes is called **corrosion** (Field, 2002).

Environmental conditions control at what rate weathering processes will operate and what landforms that will develop as a result of it. Weathering is by Summerfield (1991) defined as "the adjustment of the chemical, mineralogical and physical properties of rocks in response to environmental conditions prevailing at the Earth's surface". The parameters that in general determine the weathering process are: (1) type of earth material, (2) pressure, (3) temperature and (4) presence of water and air (Allaby & Allaby, 2003). The weathering process can be divided into two sub-processes that are distinct in theory but rarely operate solitary in nature. The two processes are chemical weathering and physical weathering. Chemical weathering simplified concerns processes where chemical reactions occur and new minerals are formed, while in physical weathering only physical changes occur (Summerfield, 1991).

Landforms that directly relate to weathering are in general minor, but in some **lithologies** they are highly developed, because of the property of the lithology

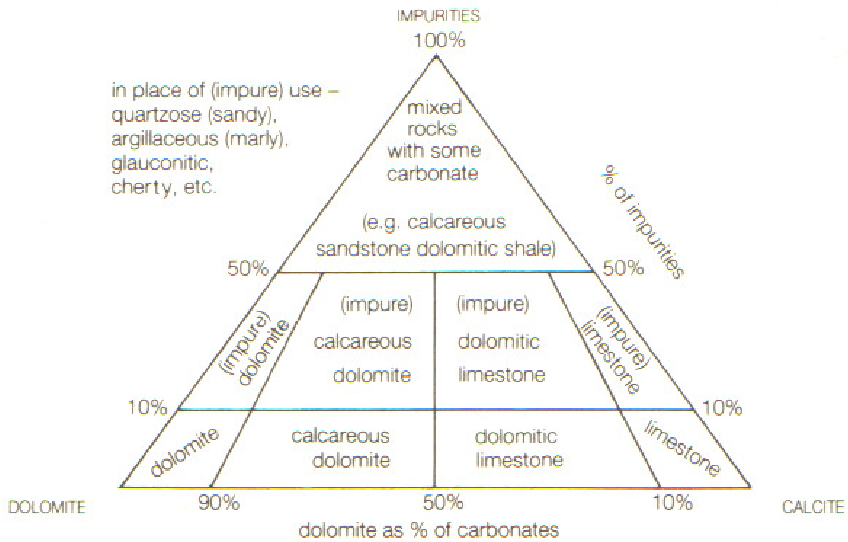

Figure 3. Classification of carbonate rocks according to Leighton and Pendexter (Bögli, 1980).

concerned. One type of lithology where the action of weathering creates distinctive and large land formations are certain types of sedimentary rocks such as limestone and dolomite.

Limestone is the most common chemically precipitated sedimentary rock. Limestone is largely composed of the mineral calcite, which is a modification of calcium carbonate ($CaCO_3$). **Dolomite** is a chemically precipitated sedimentary rock that is constituted of calcium-magnesium carbonate ($CaMg(CO_3)_2$). Because of the similar chemical constitution of the two rocks they are closely related and together limestone and dolomite constitute a group called *carbonate rocks* (Strahler & Strahler, 2005). The dispersion of carbonate rocks is variously estimated to constitute from five percent to ten percent of the world's sedimentary rocks (Jennings, 1985).

Carbonate rocks are rocks that are formed when mineral compounds are deposited from sea water in the form of salt solutions. Ions in solution form together and create mineral matter that is thus separated from the saltwater solution. The process is called **chemical precipitation**. Chemical precipitation can also occur in lakes that are situated in desert climates and are salty enough (Strahler & Strahler, 2005).

To be called a carbonate rock at least half of the minerals that constitute the rock has to be carbonate and to be considered pure a carbonate rock needs to be constituted of at least 90% calcite (Jennings, 1985). Calcite is a carbonate mineral and the most stable **polymorph** of calcium carbonate ($CaCO_3$). The distinction between different carbonate rocks is mainly made up by the rocks proportion of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). This classification according to Leighton and Pendexter is shown in figure 3 (Jennings 1985, Bögli 1980).

The difference between limestones and dolomites is not easily detected without a chemical analysis and thus the layman often can't distinguish them in field. The properties of karst morphology in both rock types is also very similar and therefore the rocks will not be separated further in this paper, and when referred to limestone in the text, dolomites are implicated as well.

The purity of a rock influences its ability to karstify. Limestones or dolomites have to be pure and compact in order for karst to develop. If the rock is impure, the karst processes can be hindered or altogether fail to appear. The structure of the rock, that is the distribution and arrangement of the elements of a rock, is also thought to influence the ability of a rock to karstify. Rocks that have a fine crystalline structure appears to have a greater ability to karstify than rocks with a coarser structure (Bögli, 1980). A third property that influences the formation of karst in a rock is the permeability of the rock. Permeability is the ability of porous materials to have fluids move through them and it is described in more detail in sections *3.2.2 Water movement in karst* and *3.3.4 Principles of Ground Water Movement*.

The permeability in turn is a function of the bedding, jointing and porosity of a rock. The type of the bedding-plane in the rock influences the permeability of it – if the bedding e.g. has served for tectonic movements it becomes more permeable since it then gains properties similar to faults. The jointing of a rock is of single most importance for the permeability of a rock. Joints in the rock both influence the surface appearance of the rock and the underground drainage in karst which is dependent on open joints. A porous rock is permeable, although this property is of minor importance when compared to e.g. jointing (Bögli, 1980).

The single most important process in the formation of karst is the chemical dissolution of the rock, which occurs through reactions in the interfaces of air and water and rock. The chemical dissolution of carbonate rocks can be, and usually is, summarized with the formula: $CaCO_3 + H_2O + CO_2 \Leftrightarrow Ca(HCO_3)_2$. The formula describes how calcium carbonate reacts with water and carbon dioxide (Helldén, 1974). The chemical dissolution can be described in more detail by six processes that occur both in dissolution and at the interfaces of air – water and water-rock. All reactions in the dissolution process are reversible and closely connected to each other and all steps should be thought of as dynamic (Bögli, 1980).

(1) $CO_2 + H_2O \Leftrightarrow H_2CO_3$

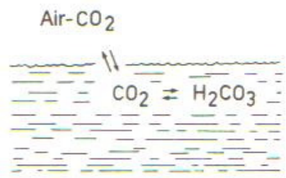

Figure 4. Physically dissolved carbon dioxide reacts with water, which results in carbonic acid (Bögli, 1980).

During precipitation carbon dioxide in the air becomes physically dissolved in water. The physically dissolved carbon dioxide reacts with water and is hydrated which results in carbonic acid.

(2) $H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$

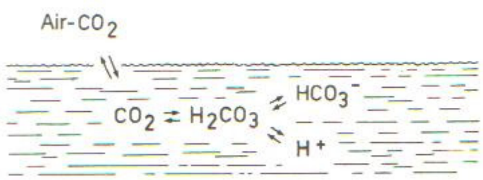

Figure 5. The dissociation of carbonic acid into hydrogen and bicarbonate ions (Bögli, 1980).

The carbonic acid is decomposed by dissociation. In this first step of the dissociation carbonic acid is dissociated into hydrogen and bicarbonate ions.

(3) $HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$

This is the second step in the dissociation of carbonic acid where bicarbonate is dissociated into hydrogen and carbonate ions. This reaction can however, according to Bögli (1980), because of its small proportions be neglected at pH-levels lower than 8,5.

(4) $CaCO_3 \Leftrightarrow Ca^{2+} + CO_3^{2-}$

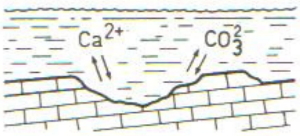

Figure 6. Calcium and carbonate ions are released from the limestone (Bögli, 1980).

This fourth step of the chemical dissolution is the first one to occur at the interface of water and rock. From the rock (calcium carbonate) calcium and carbonate ions are released.

(5) $H_2O \Leftrightarrow H^+ + OH^-$

Water is dissociated into hydrogen ions and hydroxide. As in the case of step (3), this step can according to Bögli (1980) be neglected as the low pH-values needed for dissociation in high portion are hardly ever reached.

(6) $CO_3^{-2} + H^+ \Leftrightarrow HCO_3^-$

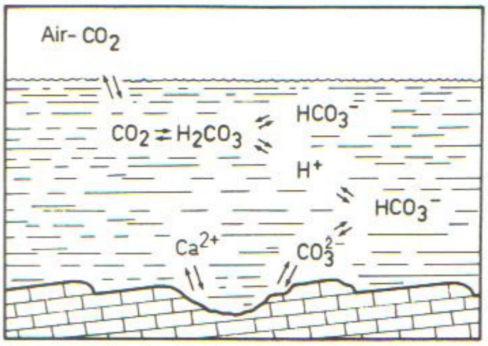

Figure 7. Carbonate and hydrogen ions created in previous steps of the dissolution process react and result in bicarbonate ions (Bögli, 1980).

The carbonate ions created in the physical process of step (4) associates with the hydrogen ions from the dissociation process of carbonic acid (step (2)).

This last step disturbs the equilibrium of the solution along the interface and processes and steps in the dissolution process are renewed in order to restore the equilibrium.

3.2.2 Water Movement in Karst

As said before, karstic landscapes are more permeable than many other landscapes with another lithology. The pathways of waters are therefore in many ways different in karst than in other types of landscapes. The maybe greatest difference from karst to other landscapes is the drainage of the landscape.

When water falls as precipitation to the ground it mostly finds its way to the sea by surface drainage – often moving as overland flow until it reaches a stream, lake or river that drains the water to the sea (see section *3.3.1 The Hydrological cycle and the water table*). The high permeability of karst alters this surface drainage as underground drainage often takes over the task of leading water to the sea. Surface drainage is therefore less common in karst and can be subdivided, intermittent in its incidence or even absent (Jennings, 1985). The partly different way of water movement in karst in relation to other landscapes will here be described.

In general, the following can be said about water that falls onto karst according to Jennings (1985). The infiltration of water into both soil and outcrop is rapid and substantial in karst and overland flow is restricted and seldom reach stream channels. Lastly, throughflow, which is the term for horizontal water movement beneath the land surface, has shown to be modest in karst.

The special drainage pattern that characterizes karst is, as said before, developed because of the high permeability of karst which transports significant proportions of the runoff underground into systems that are as well created by the action of that same water.

The permeability of rocks (also see section *3.3.4 Principles of Ground water Movement*) is according to Summerfield (1991) divided into three sub-groups – the **primary porosity**, the **effective porosity** and the **secondary porosity**. The primary porosity is the proportion of a rock that is occupied by voids, while the effective porosity is the porosity that in a stricter sense determines the permeability, since it describes the proportion of voids in a rock that are connected to each other and thus are able to transmit water. The secondary porosity is developed through time as minerals are transported away in solution creating larger e.g. joints and fissures in the bedrock where permeability of water then can become more rapid and effective. The permeability of water in rocks therefore represent a kind of positive loop where the flow of water itself, by solutional removal of parts of the rock, creates conditions for further and more rapid both permeability and further weathering of the rock. Both the removal of calcium carbonate in solution and the permeability of the bedrock thus grow over time. To conclude, subsurface flow in karst depend on the properties of the limestone and the amount of time in which the landscape has been exposed to the effects of corrosion.

Although the surface flow in karst is modest, when comparing to landscapes on other bedrock types, surface flow of course exists, and thereby also surface drainage and accompanying landforms.

The secondary porosity explained earlier largely determines how large the infiltration of water into the bedrock will be. The infiltrated water creates underground landforms where the subsurface water is drained. In the next passages, the landforms of surface and subsurface drainage in karst will be explained.

3.2.3 Karstic Characteristics of Surface Drainage

Some karstic surface landforms are the direct product of corrosion on limestone, while others are more indirect developed through corrosion. The landforms presented here are divided into the classes **karren**, **karst valleys** and **karst depressions**.

Karren

Karren are smaller surface solution features that are very common in karst and karren in some form is present in all karstic landscapes (Helldén, 1974). They are usually in the form of furrows, fissures and cavities ranging in size from just a few millimetres up to a few meters. The different forms of karren are dependent on the manner of flow of the water on the rock. The manner of flow is in turn dependent on the type and amount of precipitation at a site, the gradient of the rock and the covering of the rock. The water can either flow over bare rock surfaces that lack a vegetation and soil cover or percolate through more or less permeable soil that cover the rock surface. The paleoclimate and the properties of the rock, both physical and chemical, also influence the karren forms as well as microbiological organisms in the soil (Helldén, 1974).

Bögli (1980) classifies different single karren forms genetically into six major groups, which in turn are divided further. The six major classes of single karren forms are: (1) **Free karren** is karren created by water flowing free and unhindered over the rock surface. The limestone is bare, i.e. lacks a soil and/or vegetation cover. Examples of free karren are *Rillenkarren, Trittkarren* and *Rinnenkarren.* (2) **Half-exposed karren** are forms created on a rock surface that is only partly covered by soil. On these patches of soil the corrosion effect is increased due to microbiological organisms in the soil and the thus present biogenic CO_2. Examples of half-exposed karren are *Kamenica* (eng: *Solution pans*) and *Solution notches*. (3) In **Covered karren** soil covers the whole surface of the rock. The course of corrosion is extensive due to the large amount of CO_2 present. Examples of covered karren are *Wave karren, Root karren* and *Cavernous karren.* (4) **Grikes** are more or less vertical joints in karst created by corrosion. They form both on covered and bare karst, and are very common. Their wideness and depth varies, but a general rule is that they, like all other karren forms, are more developed in covered karst. (5) **Karren tables** or **Tables of corrosion** are formed when wider limestone areas are lowered through corrosion when wetted by precipitation. Boulders of more impermeable rocks protect limestones beneath them, which in time creates erect pedestal features in the landscape. The pedestal and the boulder together form the karren table, which are indicators of the strength of the corrosive action in the landscape. (6) **Surf karren** are formed by corrosive action of a mixture of sea- and rainwater. They appear along limestone coast and are created as waves from the sea break upon shores and splash water onto surfaces that then are subjected to corrosion and thus abraded.

Karst Valleys

In not well developed karst, fluvially eroded valleys may often be the dominant features of the landscape (Summerfield, 1991). Fluvially eroded valleys may contain streams when still young, but most valleys in karst are either dry – i.e. they don't hold an active stream of water – or they hold water only intermittently, e.g. after longer periods of heavy rainfall. According to the Serbian scientist Jovan Cvijić's early classification valleys in karst are divided into **dry valleys**, **blind valleys**, **half-blind valleys**, **pocket valleys** and **allogenic valleys** (Helldén, 1974).

Dry valleys are said to be the most common valley types in karst (Helldén, 1974). These valleys are lacking water completely or can hold water only temporary. In general, most dry valleys in karst can be explained by means of water loss as a result of the increasing permeability of limestone over time. But some valley features in karst can't be explained with this general rule. Some other possible explanations for dry valley formations are: (1) initially impermeable rock covered a limestone area. The impermeable rock holds an established drainage system. When the limestone underneath the impermeable rock in time gradually is exposed, the water existing in the area could create valleys in the limestone. (2) During the past glacial periods the ground just below the surface in the limestone was perennially frozen, which made it impermeable at that time and made it possible for water at the surface to exist and cut through the limestone creating valleys. (3) The water table underground in an area has been lowered faster through time that the effect of water cutting through the ground at the surface. In this way, the valley floors are left above the water table leaving the valleys dry (Summerfield, 1991).

As mentioned before, in karst it is also common that streams are subdivided disappearing rapidly into the ground in places or appearing from seemingly nowhere at other places. Three valleys where streams are present only in parts are shown in figure 8.

In the case of a blind valley (A) water is only present at the higher part of the valley until the stream reaches a **sinkhole**, where

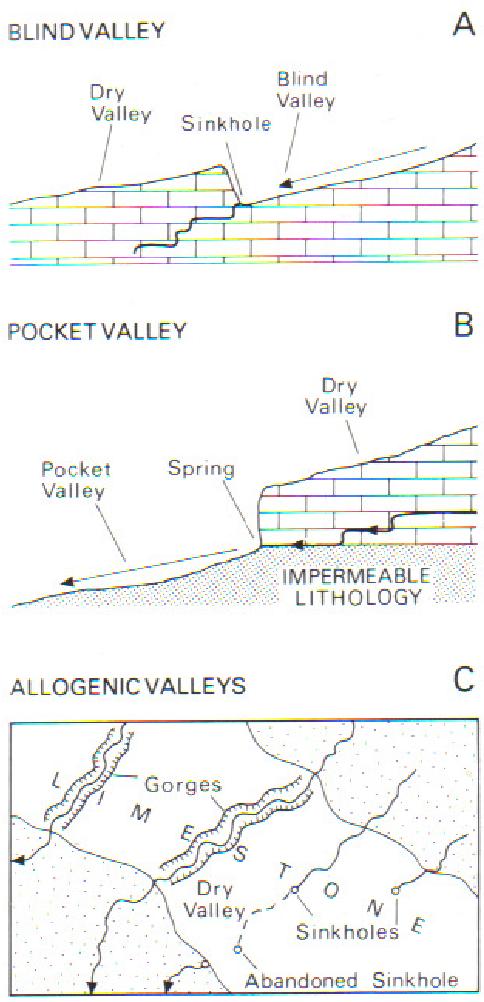

Figure 8. Three types of dry valleys; blind valley, pocket valley and allogenic valley (Summerfield 1991).

the water disappears underground leaving the lower part of the valley without any flow of water (dry valley). The term *sinkhole* can in American be used as a term both for a point where a stream or river disappears underground and as a more general term for closed depressions. In this section *sinkhole* is used in the first meaning of the term. Because water only flow upper-valley from the sinkhole, this part of the valley floor over time often becomes significantly lowered due to higher rates of weathering and erosion, leaving the part down-valley from the sinkhole, the dry valley, higher. In time, the once uniform valley floor will become separated by a large height difference. The upper part of the valley is in this case called a blind valley. A half-blind valley is similar to the blind valley with the difference that under conditions of high tide the sinkhole, that under normal conditions transport the water underground, can't take in all the amount of stream water. Parts of the stream thus move beyond the first sinkhole to a sinkhole further downstream. Because of this, a half blind valley can be said to be divided into two parts; one valley part active under normal conditions and one smaller valley situated downstream and only active under conditions of high tide.

In the case of a pocket valley (B) the situation could in parts be said to be reverse. Here water emerges from a junction of an impermeable lithology and a thick overlying limestone. The water flows underground in the limestone and when it emerges as a spring at the end of the limestone it suddenly gains flow velocity, which leaves a part of the lithology down-valley of the spring affected, i.e. this part gets hollowed out by the water in time. This formation is called a pocket valley.

When eater streams enter an area of limestone from an area of impermeable lithology allogenic valleys (C) are formed. The impermeable lithology bordering to the limestone can hold permanent surface water flow and when this same flow of water crosses over to limestone lithology its flow is somewhat altered. Depending on the size of the stream and the permeability of the limestone the stream will flow overland more or less far. Small streams will disappear underground via sinkholes faster, while larger streams can survive longer distances or even flow through the permeable area onto the impermeable lithology again. Valleys created this way – by streams coming from other lithologies that hold water permanently – are called allogenic valleys and their size and length are depending on the strength of the water stream and the permeability of the limestone that they enter.

Karst Depressions

Karst depressions are depressions in karst created by the direct action of corrosion or by the indirect action of corrosion via collapse and subsidence of the limestone into cavities in the ground (Bögli, 1980). The depressions in karst can be smaller or larger. Common smaller closed depressions in karst are **dolines** and **cockpits**. Larger closed depressions in karst are called **poljes**.

Dolines are according to Bögli (1980) the most common karst features found in every karst landscape. They are depressions whose diameter often is larger than their depth. The diameter of a doline can range from a few meters up to 1000 meters, and the depth often varies between a few decimetres and 100 meters (Helldén 1974, Bögli 1980). A genetic classification dolines divides them into *solution dolines, subsidence dolines* and *collapse dolines* (Bögli 1980).

Figure 9 shows different doline types. **Solution dolines** (A) are created as water infiltrates soil and when it reaches the limestone it enters the interstices in it and widens them through corrosive action. In this way limestone is dissolved and the widened interstices lead to sinking, and finer material is transported away. Some field work have shown that the soil cover on the limestone is critical for further deepening of the doline (Bögli 1980). Precipitation is the most important factor in the development of solution dolines. **Alluvial dolines** (B) are created when overlying loose material subside into the enlarged interstices in the limestone, created through widening and dissolution of water.

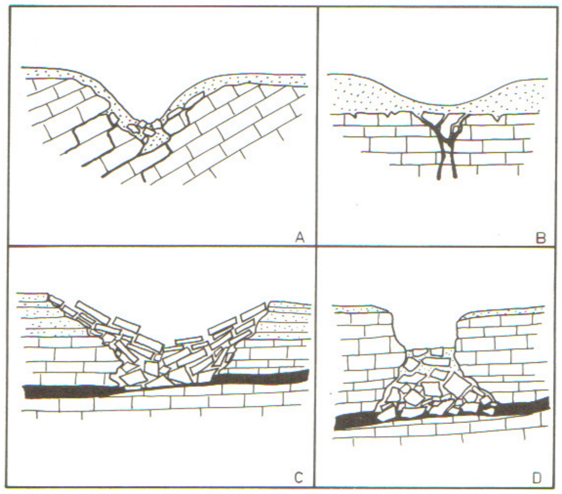

Figure 9. Solution doline (A), alluvial doline (B), subsidence doline (C) and collapse doline (D) (Bögli, 1980).

Subsidence dolines (C) are created as a surface mass of rocks and/or soils subsides slowly downwards into cavities created by dissolution of the limestone. If the doline is created by a rapid subsidence of the ground over a cave, often even on one single occasion, the doline is called a **collapse doline** (D).

Cockpits are karst depressions evolved in tropical climates. The depressions are star shaped in contrast to dolines in temperate climates, which are more circular in their form. The floor of a cockpit is concave while the surrounding hill slopes, called *kegeln*, have steep and convex sides.

Poljes are, as said before, the largest closed depression forms in karst. The word "polje" in most Slavic languages means "field". Poljes have a flat bottom floor which in many cases is covered with fluvial deposits. The size of poljes may vary greatly, from areas smaller than 0,5 km^2 to areas as large as 1000 km^2 (Bögli 1980, Field 2002). Most poljes are elongated in form and they show complex hydrogeological characteristics. The drainage in poljes may be either swallow holes or surface streams. If the polje has subsurface drainage it is called a *closed polje*, and if it has some surface drainage it is called an *open polje.* Characteristic features in many poljes are so called *hums*, isolated and cone shaped hills in limestones. They are remainders of the formation of poljes. It is common that during times of greater precipitation poljes get flooded since the sinkholes and the subsurface drainage system can't drain the excessive water. Often the sinkholes in poljes even become sources of water, functioning as springs, at these times. Features that can both function as sinkholes and springs are termed *estavelles.*

3.2.4 Karstic Characteristics of Subsurface Drainage

It has been shown by a large amount of field data collected that both diffuse flow and conduit flow occur in karst (Summerfield 1991) (see section *3.3.4 Principles of Ground Water Movement*). Their relative importance on a site depends both on the type of topography and lithology present. At sites where the limestone is more porous and the landscape is relatively plain with a lithology lying more horizontally diffuse flow is more common, while the movement of water could be explained better with conduit flow in sites which have a high relief and where the limestone is less porous (Summerfield, 1991).

Karst is very suitable for the formation of **caves**. A cave is by Field (2002) defined as "a natural home in the ground, large enough for human entry". This definition can seem rough, but coincides well with definitions by other renowned scientist (Bögli 1980, Jennings 1985 and Summerfield 1991) and eliminates artificial cavities formed by e.g. tunnelling and at the same time it covers the great varieties of natural existing caves well.

In order for a cave to develop some criteria need to be met according to Jennings (1985). The karst rock where the cave will be produced needs to be permeable "enough" – that is not too porous neither too cemented. The rock has to be relatively pure, i.e. not have such an amount of insoluble particles in it which could hinder the initial process of cave forming. At the same time the rock shouldn't be more porous than needed and "weak" in that sense, since it needs to be able to hold the walls and the roof of a cave. Besides the rock properties, water in a liquid state that can dissolve the rock needs to be present as well as the site at which a cave is created needs to have some relief in order to provide the hydraulic gradient needed for transportation of the water and its solutes.

Caves are found in a wide range of different sizes, shapes and properties. The size of a cave can go from only a simple cavity in the rock to great underground complexes. These caves of more complicated construction are termed cave systems according to Bögli (1980) and will in this paper as well be termed that way. The number of caves developed in a rock is also variable. Some rocks hold a single or a few cavities, while others are pierced throughout with caves and cavities of various sizes. An example of a great single cave chamber is the Sarawak Chamber in the Good Luck Cave (Lubang Nasib Bagus) in the federal state Sarawak in western Borneo – i.e. the part that belongs to Malaysia. This chamber is 280 meters high, 700 meters long and 400 meters wide. Another example of a great and complex cave system is the Hölloch Cave, Switzerland. Caves can be found in almost all parts of a rock, from beneath the water surface to the top of a rock and the extension of caves are in general more commonly horizontal than vertical (Jennings, 1985).

The definition of a cave holds in it a presumption that a person can fit in it. To be able to do so the cave needs to have an entrance, through which a person can reach the cavity. The entrances to caves are, as

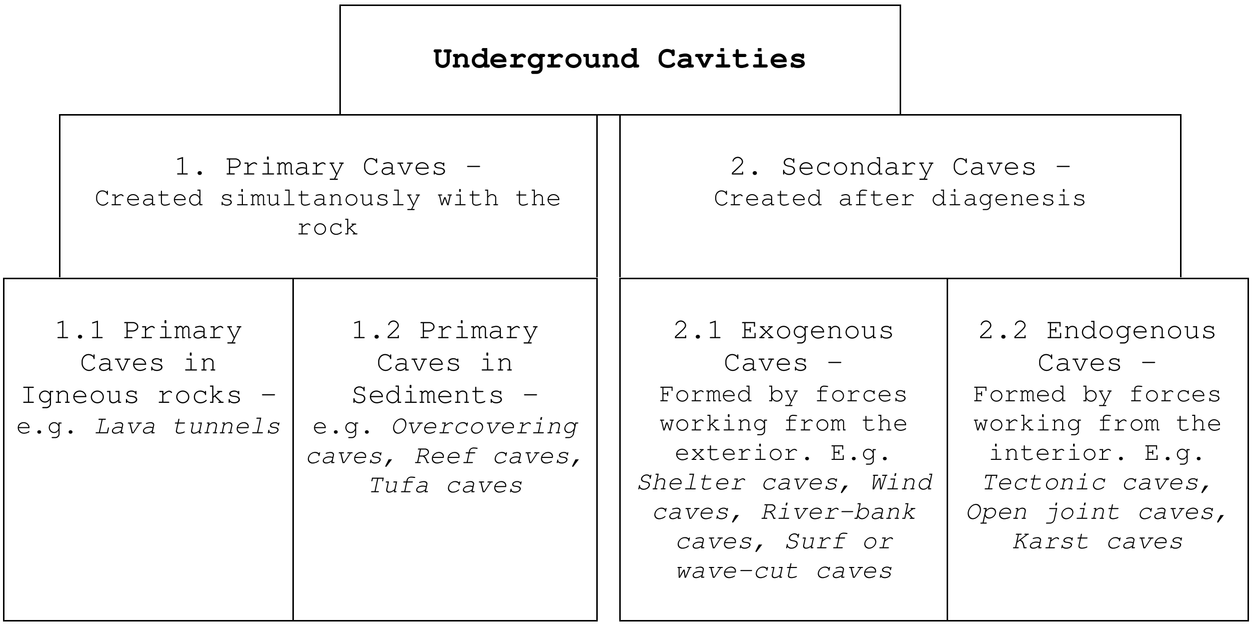

Figure 10. The genetic classification of underground cavities of Alfred Bögli (1980) (Raguž, 2008).

most other properties of a cave, variable both in size and position. Naturally entrances to caves occur in a range from horizontal openings on the side of a rock to vertical shafts. Many caves also have artificial anthropogenic entrances, either by removal of rock deposits that blocks a natural entrance, or even by mining.

The relation between caves and water is also different from case to case. Some caves are filled with water, partly or completely, while others are quite dry. In some cases this relation vary over time making the cave waterfilled intermittently, just as some surface landforms, in others the availability of water is more constant. This change in water availability in caves doesn't need to come from outer conditions, but the change in water availability is a simple outcome of the waters nature of constantly finding lower pathways for travelling through karst. Karst caves often consist of cavities, functioning as pathways for water on separate levels, where the lowest level often still is actively holding water (Jennings, 1985).

One of the available classifications of karst caves is given by the relation of water movement through them. This descriptive classification presented by Grund in 1910 (Jennings 1985) will here be used to present and explain different cave types in karst.

The terminology in this classification is clear, simple and figurative. The caves are divided into *through-caves*, *inflow caves*, *outflow caves* and *between-caves*.

A **through-cave** is a cave where a stream of water can be traced from its engulfment into a rock and then all the way to its outflow. With **inflow caves** the stream can be followed from its inflow to a distance downstream the cave where an obstacle is found which stops further tracing. An **outflow cave** can, as the name itself suggests, be said to be the opposite of an inflow cave. Here, a stream can be traced upstream into a cave until it reaches an obstacle. Finally, a **between-cave** is a cave that has an inflow, but the stream can't be traced further to the surface, neither downstream nor upstream.

Although karst caves may be the most frequent in occurrence - they are actually thought to be more frequent than all other cave types together according to Bögli (1980) - it has to be mentioned that caves also are formed in other lithologies and through other processes. The time and space frame of this paper delimits a broader presentation of these, but two of them will be mentioned shortly in order to serve as examples.

Tectonic caves are caves that are formed after **diagenesis** and by forces working from within the cave, so-called endogenic forces. For tectonic caves these forces are, as the name implies, tectonic and other processes such as corrosion or erosion are of minor importance for the creation of these caves. Examples of tectonic caves are located in Yorkshire, England, where open fissures can be found. *Lava caves*, also known as *lava tubes* or *tunnels* since the physical appearance of most lava caves resemble a tube or tunnel, are caves in igneous rocks. Lava caves are created simultaneously with the rock itself, and thus has nothing to do with water movement through the rock and affiliated processes. Lava caves are created as molten material in a rock flows away under a roof of hardened lava and leaving an open tunnel behind. Lava caves can e.g. be found on the islands of Lanzarote, Island and Hawaii (Bögli, 1980). For a general genetic classification of underground cavities after Bögli see figure 10

The interior of caves are of a very conservative nature, which often preserves forms and different bedrock deposits that are developed in it for longer time periods. The nature of a cave hinder most erosional forces as well as the stable atmosphere in a cave minimize weathering actions. These conditions enables formation and preservation of some impressive depositional forms, e.g. various **speleothems** such as **stalactites** and **stalagmites** - cave formations known to many. Because of the conditions in a cave, cave deposits also provide scientists with valuable and historical traceable data, of which sort is not found in many other environments. This paper will not further go into cave deposit features.

Another characteristic feature of karst landscapes are **karst springs**. It may be disputed whether springs should be presented in this section of subsurface characteristics of karst since they are visible at the surface, but since the outlet of a spring simply is a visible endpoint of a much larger subsurface system I see them as belonging in a higher degree to subsurface than to surface karst and therefore present them in this part.

Karst springs are water outlets in karstified limestone, emerging from hydrologically active cavities. Karst spring can be both surface and underground features (cave springs) and can often be large features with great discharges. A classification according to the origin of water divides karst springs into *emergence springs, resurgence springs* and *exsurgence springs.* **Emergence spring** are larger karst springs where the origin of the water is not known. The term is also usually used as a general term for both resurgence and exsurgence karst springs (Field 2002). In **resurgence springs** water streams that have submerged from the surface via sinkholes emerge at the surface again. **Exsurgence springs** have an outflow of water of autochthonous origin.

Springs occur in both confined and unconfined conditions (see *3.3.3 Aquifers*). In confined aquifers they occur because the ground water in an area is under pressure, which can – if large enough - push the water upwards to emerge as a spring at the land surface. Under unconfined conditions springs occur when water travels from higher to lower elevations.

3.3 Karst Hydrology

In order to better understand further line of arguments and descriptions of karst hydrology and its characteristics, some fundamental hydrological notions will be presented in the beginning of this section.

3.3.1 The Hydrological Cycle and The Water Table

Figure 11 shows a simplified picture of the circulation of the world's waters – the Hydrological cycle. Water circulates between the earth's four great realms – the **hydrosphere**, **atmosphere**, **biosphere** and **lithosphere**. The world's water supply is unevenly distributed among the realms. Saline waters in the world oceans stand for 97,2% of the world's total water supply, 2,14% of the water is stored in solid form in the world's ice caps and glaciers, 0,61% of the total world water supply is the ground water, the surface water constitutes 0,009%, another 0,005% is the soil moisture while the atmosphere holds 0,001% of the total water supply of the world (Fetter, 2001). As the name itself implies the hydrological cycle has no beginning and no end, but since most water is stored in the oceans this is the part of the cycle where I will start my description of the cycle.

As mentioned before, a large majority of the total water supply of the world is constituted by saline waters in the oceans. This water evaporates when heated. When evaporated the water changes form from liquid to gas and travels upwards into the atmosphere as water vapour. When evaporated, the salts of the sea are left behind and thus the water is purified. Other water bodies such as lakes, rivers and reservoirs also evaporate water, but also less open and obvious water sources evaporate. Such sources are e.g. the upper layer of soils where water is detained. Transpiration by vegetation of the biosphere is another source of water vapour in the atmosphere. With a common name **evaporation** and **transpiration** are called evapotranspiration. Evapotranspiration is the process that feeds the atmosphere with water vapour (Fetter, 2001).

The water vapour in the atmosphere can, under certain conditions, transform back to solid or liquid form and fall down to the ground as **precipitation**. Water fallen as precipitation and then temporarily stored as ice, snow or water in puddles or glaciers is called depression storage. But most precipitation still reaches the ground. Here, water will either flow over the land and into a stream or river or seep into the ground if the surface is porous. Water flowing over the land surface is called **overland flow**, while the process where water seeps into the ground is called **infiltration**. **Runoff** is the total flow of water in a stream. Water that is stored in open water bodies, such as ponds, lakes, rivers, streams and oceans is called surface water.

In the uppermost layer below the ground surface there is both air and water in the soil pores. This zone is called the **vadose zone** (or the zone of aeration). Here the water pressure is lower than the atmospheric pressure. The water pressure is developed from the amount of fluids that are above a certain point (Fetter, 2001). Since water above a point decrease as ground surface is approached, the highly situated vadose zone has a relatively low pressure. In this area the voids in the ground may be and become dry from time to time and from place to place. Rain or soil water in this zone is divided into **vadose seepage**, which is water that percolates downward, and **vadose**

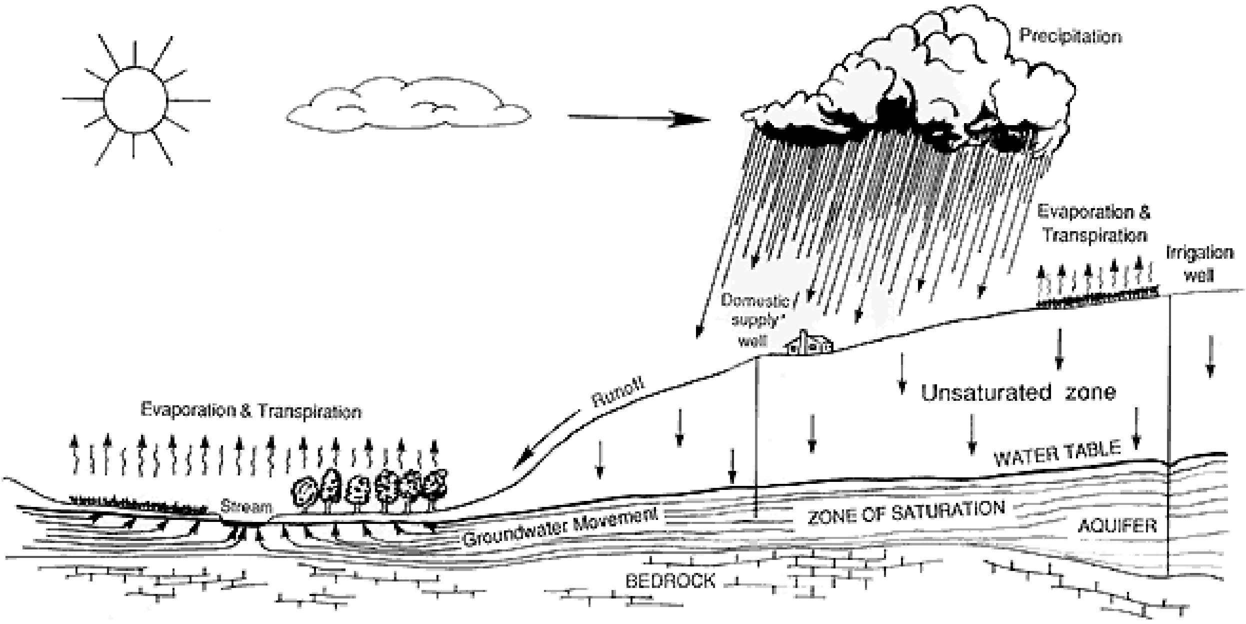

Figure 11. The Hydrological Cycle (University of Florida, Department of Geological Sciences, 2008).

streamflow, which is water that flows openly and most often laterally. In vadose streamflow the flow can be downwards as well, but it is lateral at least as often as it is directed downwards (Jennings, 1985).

Some of the water in the vadose zone is pulled down deeper into the ground by gravity – this process is called **gravity drainage**. At a certain depth the soil is saturated with water, i.e. there is no air in the soil pores but all are filled with water, and water pressure is greater than the atmospheric pressure. This zone is called the **phreatic zone** (or *zone of saturation*) and the **water table** is the upper limit of this zone, i.e. the boundary between the vadose zone and the phreatic zone. At the water table the pressure of water in pores is equal to the atmospheric pressure.

The movement of water from the vadose zone to the saturated zone is termed **percolation**. Water stored in the phreatic zone is called **ground water**. The lower limit of the phreatic zone is a fully impermeable surface. The movement of the ground water through the soil and rocks towards an outlet, either in the form of a spring or as seepage, is termed **ground water flow**.

Ground water in karst differs in some ways from ground waters in general, and it has therefore in some circles been discussed whether or not waters in karst can be termed *ground water* (Bögli, 1980). Since the question only considers the size of cavities in the ground, pores and e.g. joints both considered cavities, I will here present some distinctive features that could characterise karst ground waters and then use the term *ground water* accordingly to the description that was given above, i.e. part of the subsurface water that is in the phreatic zone.

The greatest deviations of ground water in karst from ground water elsewhere comes from the fact that the ground water surface in karst is not coherent, but the water levels are individual and often divided by space. The ground water in karst is not joined together in one common body that moves as a whole. Instead, ground water in karst often moves in individual streams not seldom hydrologically independent of one another (Legrand & Stringfield, 1973).

3.3.2 The Hydrologic Equation

The water budget in an area is dependent on all parts of the hydrologic cycle, and accounts both surface and ground water. An area of land that slopes towards a single common water discharge point is a **catchment area**. The availability of water in a catchment area can be evaluated by the **hydrologic equation**. The hydrologic equation evaluates the hydrological cycle quantitatively and is expressed as:

Inflow = outflow +/- changes in storage

If outflow exceeds inflow in a catchment area the storage of water will be reduced, while the storage will increase if inflow exceeds outflow. Storages of water can be found in streams, lakes, rivers and ponds. Less obvious storages includes water in plants, water stored as soil moisture in the vadose zone, as ground water in the saturated zone. The sources of water inputs at a site can be precipitation, surface-water including both overland flow and runoff, ground water inflow and artificial import of water into the area. The sources of water outputs from an area can be surface water runoff as well as ground water outflow. Other output sources are evaporation of surface waters, evapotranspiration from the land surface and artificial removal of water from a site (Fetter, 2001).

3.3.3 Aquifers

An **aquifer** is a geologic formation, part of a geologic formation or many formations grouped together that can hold a usable amount of water or from which the same can be extracted (Field, 2002). In fewer words an aquifer is a reservoir of ground water.

A karst aquifer is fed with water from four different sources. Precipitation can reach the aquifer either falling directly on bare limestone, or falling on soil and after percolation reaching the limestone. The aquifer is also fed with water from surface rivers and streams and by condensation water (Bögli, 1980).

Aquifers are in general divided into two different aquifer rock types: **consolidated** and **unconsolidated** rock. Unconsolidated rock aquifers are constituted of granular material, while consolidated rock aquifers are aquifers of different rock types, of which limestone is a part. Some consolidated rock aquifers yield low amounts of water because of their impermeability, but the characteristics of limestone and karst holds possibilities for large outputs of water flows (Cech 2005).

Aquifers are further divided into **confined** (also called *artesian aquifer*), **unconfined** (also called *water table aquifer*) and **perched aquifers**. Confined aquifers are overlain by a **confining layer.** A confining layer is a geologic element that is impermeable or have very low permeability. The confining layer restricts the movement of ground water and puts it under pressure. An unconfined aquifer is often close to the land surface and constitutes highly permeable material. The perched aquifers finally, are aquifers that have a lens-formed formation of low permeability in otherwise permeable material. Water moving downwards through the vadose zone will accumulate on top of this lens, thus creating a saturated zone that lies above the general water table of the area.

Karst aquifers are characteristic for the open conduits that constitute them. The open conduit system in a karst aquifer allows water to flow through low resistance pathways and often the water creates new pathways for itself in the high permeable rocks. This creation of new flow paths in karst are in a geologic time-scale rapid processes (White, 2002).

3.3.4 Principles of Ground Water Movement

Under natural conditions and without any obstacles water strives towards lower elevations due to forces of gravity. In an aquifer, however, the real movement of water flow is determined not only by water's natural movement, but by local conditions such as lithology, stratigraphy as well as the structure of the geologic deposits in the ground. Principles of ground water movement can be described by means of *porosity* and *permeability*, *hydraulic conductivity*, *hydraulic head*, *hydraulic gradient* and *transmissivity*.

Porosity is the ratio, most often expressed in percent, of the volume of pore spaces in a rock or soil to its total volume while **permeability** the ability of porous materials to have fluids move through them. In karst, porosity of aquifers are often low but permeability is often high. The rock itself is impermeable, but the voids and large openings in the rock allows high velocities of water movements in these aquifers. For further classification of permeability types see section

Hydraulic conductivity, also called the permeability coefficient, is the actual flow of fluid through a material and is expressed as a rate of discharge in meters or feet per day. A common way of measuring hydraulic conductivity is by means of a so called **tracer test**. In a tracer test the time necessary for a dye to travel from one monitoring station, often e.g. a well, to another is measured.

Hydraulic head is the height of a water column that can be supported by the water pressure at a given point and time of measurement. The hydraulic head is the driving force of ground water movement and ground water always moves from a place of higher hydraulic head to a place of lower hydraulic head. The hydraulic head therefore makes water not only move downward, as it would if it would only be under the forces of gravity, but both sideways and upwards as well.

Hydraulic gradient is a function of the hydraulic head and is expressed as (Cech, 2005):

$$\mathbf{i = dh / dl}$$

where **i** = hydraulic gradient
dh = the change in hydraulic head between two points at the top of the ground water table
dl = the length of the distance between the two points

The hydraulic gradient is the slope of the top of the ground water table in an aquifer and it indicates the movement of the water. The hydraulic gradient has to be of a nonzero value for the ground water to move. If the hydraulic gradient is zero, the water table is flat, and no water movement will occur. Ground water moves, as said before, from areas of higher hydraulic head to areas of lower hydraulic head, while the gradient's direction goes from lower to higher hydraulic head. This means that the flow of ground water is parallel to the hydraulic gradient, but in opposite direction. The maximum flow of water in an aquifer usually is in the direction of largest hydraulic gradient.

Transmissivity is the measure of the rate at which water moves horizontally in an aquifer unit and is expressed in square meters or feet per day. Transmissivity equals the hydraulic conductivity of an aquifer multiplied by the saturated thickness of the aquifer.

One well used concept amongst hydrologists when wanting to monitor water movement in an aquifer is **Darcy's law**. Darcy's law is a mathematical formula for showing the discharge of water through a uniform porous bed of sand and is expressed as (Cech 2005):

$$\mathbf{q = K \cdot i}$$

where **q** = discharge per unit area
K = hydraulic conductivity
i = hydraulic gradient

The water flow in a karstic aquifer can generally be divided into two major types of ground water flow. The first is **conduit flow** and the second is **diffuse flow**, which both present extremes in a continuum. The use of these terms has become widely used in the literature, and are therefore here presented, but they should – as mentioned before – be considered as extremes in a continuum and therefore as a simplified description of the real state of water flow. The terms arose from work of Shuster and White in 1971, where they examined karst springs and found two distinctive types of springs which they named *diffuse flow springs* and *conduit flow springs*. It was later whereas found that by chance the investigations were performed in such hydrological settings that the responses belonged to opposite ends of a continuum (White, 2002).

Water flowing in a conduit flow system is characterised by high variability. The system has a high ratio between maximum and base-flow discharge. This means that the discharge of water is irregular and responses to precipitation are rapid, powerful and the flow of water in these systems is generally **turbulent**.

Water movements in diffuse flow systems are less irregular and the ratios of maximum discharge and base-flow discharge is low. The flow of water in these systems is generally **laminar** and the response of water discharge to precipitation is not as rapid as in conduit flow systems. In general conduit flow systems are found in mature karstic landscapes, while diffuse flow systems are found in aquifers in less well developed karst (Quinlan 1989).

If in a diffuse flow system, the water movement in a karst aquifer can in many ways resemble the movement of water in any other granular aquifer, since Darcy's law is operative, but if in a conduit flow system the water movement differs significantly from water movements in other aquifers – e.g. being faster, more irregular and turbulent (Quinlan 1989). Conduit flow of ground water has many similarities to surface water flow, and it is therefore necessary to have not only ground water but also surface water concepts in consideration when observing these flows (White 2002).

3.3.5 A History of The Theory of Karst Hydrology

The theory of how water behaves and travels in Karst, that is the theory of Karst Hydrology, has had various developments in different scientific circles. The greatest controversy in this theory amongst scientists through history has been how well Karst landscapes can be compared to other terrains when looking at water and its movement. In Anglo-American literature for example, the Hydrology of Karst was for long considered similar to hydrology in any other terrain (Jennings, 1985). This in other words meant that the notion of the water table, was used unmodified for studies and descriptions of Karst. Two early and renowned scientists in the area of karst and karst hydrology, the

Austrian Alfred Grund and the Serbian Jovan Cvijić, were two to use the water table for describing Karst Hydrology in the early 1900's and the late 1800's, respectively. Their first theories, based on the water table, described Karst Hydrology by dividing the terrain involved into three different hydrological zones; *the upper vadose zone*, *the lower phreatic zone*, and *the intermediate zone* (Jennings, 1985).

The upper vadose zone and the lower phreatic zone in this description coincides with the *vadose zone* and the *phreatic zone* described in section 3.3.1 *The Hydrological cycle and the water table*. The last hydrological zone discerned when describing karst hydrology with the original concept of the water table is the intermediate zone. In this zone the water table rises and falls, which among other things results in intermittent filling up and emptying of water in caves (Jennings, 1985).

The theory of the water table was originally developed for water travelling through sand and gravel (Jennings, 1985) and it was early found by other scientists, that had directly observed water movement in karst, that the karst ground in many aspects differed from this simplified picture of water movement in the ground, and they therefore found that the notion of the water table wasn't adequate for karst.

Katzer and Martel were two scientists that in the early 1900's opened the path for a new view and school rejecting the notion of the water table and describing the hydrology of karst with numerous conduit systems operating independently. The conduit systems were compared to rivers, but instead of operating over a single surface like "ordinary" rivers, these systems should be thought of as operating in a three dimensional space (Jennings, 1985). In this view part of the water flowing in karstic systems flow freely and in part filling up caves and other cavities in the ground. The water flows underground due to gravity alone. When the water comes across an obstacle in the underground systems it is pushed upwards in some cases, creating risings of water.

Therefore, in this theory of independent conduits instead of water tables the notion of *rest levels* for water are presented.

In further developments of theories on karst hydrology attempts were made to bring together the both earlier theories and comprise views were developed. Systems of water in karst weren't seen as having a single common water table, and as well not as a system consisting of numerous independent conduits not cooperating. Cvijić presented a compromised view as early as in his later works in 1918 and 1960, and among others Otto Lehmann continued his work in trying to develop a compromising view of the two previous theories. He did this using an evolutionary basis (Jennings, 1985).

Later, scientists have further developed compromised views of karst hydrology, mostly based on empirical evidence. Basically, in these comprised views karst hydrology is described as a system of many separate input points, but underground these streams merge into common conduits and finally reach outlets in a single or a few flows (Jennings, 1985).

The degree of intercommunication between conduits in a system depends on the evolutionary stage of the landscape. Through the evolutionary stages of karstic landscapes there is, according to the view of Lehmann (Jennings 1985), a gradual widening of passages and removal of different barriers, which leads to a state where limestones in time are considerably reduced in size. In this mature stage of the geomorphologic evolution of the karst something similar to a water table is thought to be established (Jennings 1985).

In recent decades, the recognition of the close relationship between surface waters and ground waters in karstic regions has been illuminated and has been widely discussed (White, 2002).

Finally, in general it can be said that in the history of karst research the trend has been that the works on karst has gone from being more closely related to geomorphology to works with a higher degree of aspects of hydrology (Legrand & Stringfield, 1973).

3.4 Problems and Possibilities of Water Management in Karst

The high permeability of karst has major impact on the landscape where it resides and makes it an interesting, different and challenging area for both water and other management issues and decision-makings. Practical problems specific for karst are usually said to be (1) shortage of water supplies and difficulties of predicting the same; (2) surface streams are rare; (3) unstable ground; (4) leakage of reservoirs present at the surface; and (5) unsuitable environments for waste-disposal (Legrand & Stringfield, 1973).

(1) The permeability of the aquifers in most karst areas is either too high or too low for a stable ground-water supply to develop. If the permeability of the rock is too low, water will not be able to percolate into the aquifer but will most likely be lost as overland flow to areas of higher permeability. All the same, a too high permeability will also result in water scarcity, since storage of water entering an aquifer will be limited or insufficient. These conditions occur because the movement of water in fissures and cavities can be so rapid that the flow of water isn't slowed down and thereby stored. Instead water is quickly lost to the sea.

The permeability is often unevenly distributed in karst. This condition creates a positive loop of water movement in certain paths. The uneven permeability of the rock tunnels water to certain fissures, which then are enlarged by the workings of water and this in turn enables even easier pathways for water movement. Thus, water in karst tend to flow together and accumulate in large cavities underground and discharge at the surface as single or few large springs, often widely spaced. The positive aspect of this condition described is that wells that reach down to such a cavity underground, will yield a great amount of water, in most cases far greater than wells in other aquifers.

The problems in karst aquifers come with knowing and predicting where the water will accumulate, because techniques used in other aquifers are not readily applicable in karst. Permeability decreases fast with depth in most karst landscapes, so the fresh-water zone is often very thin and shallow. In caves and cavities underground some thin layer of water often exists. This water is, however, mostly old, which makes it stagnant and salty (Legrand & Stringfield, 1973).

If managed the right way, the large reservoirs often present in karst can be sufficient sources of water even during conditions of water deficit. A deficit of water supply in karst areas often occur during periods of low waters, i.e. periods when the inflow of water is low, because of the fast discharge of water through springs. One principle of ground water management is the concept of "loan" of water from a storage during recessional periods. Later, during periods of high-water, the storage is anew filled with water and thus recharged. This principle of water management is especially suitable for karst aquifers, because of the relatively fast refill of the storage in times of high-water (Jemcov, 2007).

In order to "loan" water from a storage, water needs to be tapped from often deep lying storages of water. For this purpose, wells are often constructed and used. The greatest concern when operating this water management principle is the risk of overexploiting the water storage, which would lead to other environmental problems, such as e.g. ground subsidence (see further down). In order to avoid overexploitation principles for proper estimations of potentials and resources available for tapping from storage needs to be established. Igor Jemcov has presented one possible method for estimating optimal exploitation capacity of karst aquifers (Jemcov, 2007). The water supply potential of a site is firstly estimated and evaluated on a ground water budget basis. Further steps taken are estimations of storage changes in the aquifer under normal conditions as well as estimations of potential expansion of the tapped sources (Jemcov, 2007). In this way, an optimal exploitation capacity of the aquifer was estimated.

(2) The scarcity of surface streams leads to difficulties in management of the existing water supplies in karst. Since no streams are present, there is a very narrow spread of water supplies in an area. The two available ways of getting a hold of water is either through wells or at the spring. Withdrawal at one site will create a deficit at the other (Legrand & Stringfield, 1973).

At the other hand, however, springs could also be viewed as the most positives attributes of karst aquifers in water management purposes. Since a large amount of the total groundwater is discharged in a single, or a few springs, the karst springs are by White (2002) compared to "a perfectly placed well in other aquifers".

Implications of scarcity of water streams could be large fluctuations in water supply in geographical limited areas, with non-availability of waters at many sites, while others have a surplus supply. What could be deduced from this condition will be further discussed in section *5 Discussion*.

(3) The large cavities existing underground in limestones can make the ground surface unstable, since the rock structure is weakened. Anthropogenic activity such as e.g. lowering of ground-water table through excessive withdrawal of water from wells, or heavy constructions on the already weakened rock can cause the ground to subside.

(4) Surface reservoirs, such as dams, often used in water management can show to have difficulties holding water in karst. This, also, is due to the high permeability of the rock that the damn is built upon. This problem is often solved by injection of large amounts of grout around the dam, thus minimizing the permeability at the site.

(5) Leakage of material at the land surface causing pollution of ground-water in karst is common according to Parizek et al. (in Legrand & Stringfield, 1973). The either very permeable or very impermeable rock surface is once again improper – this time as a part in a waste-disposal environment. If the rock isn't permeable enough, it won't be able to sufficiently accept wastes. If it's too permeable, on the other hand, the short time spent in the aquifer will not be enough for the waste to purify and the waste can this way enter a discharge point thus causing polluted water. From the same line of arguments it can also be concluded that spill or leakage of hazardous material in karst can have catastrophic effects of water quality in the same area, since there often is a lack of filtration (Afrasiabian, 2006) and the flow of waters discharge in springs rapidly and can travel long distances – making a possible contamination rapid as well as far spread (Quinlan, 1989).

A heavily debated and controversial construction of deep tunnels in close connection to Lake Michigan in Milwaukee, U.S.A, can serve as further example of management challenges in karst concerning both ground subsidence and leakage both in and out of anthropogenic constructions in karst (Day, 2003). The example can also accentuate the importance of understanding and modelling of karst aquifers for proper management. Construction problems concerning karst that were encountered in the deep tunnel projects were; rock collapses such as local falls of rocks from the walls and ceiling of the tunnels; subsidence of the ground when tunnels encountered local weaker sections in the rock, such as weaker stone beds or clay layers; and ground water intrusion into the tunnels which was shown to be the greatest and most expensive problem. In order to halt further intrusion of ground water grouting was performed along the tunnel. The grouting was however needed to be repeated several times, in order to halt the never ending intrusion and this was a costly undertaking. The intrusion of water wasn't unidirectional going only into the tunnel, but water was also shown to seep out of the tunnel, which leads to new environmental issues that needed to be dealt with, namely contamination of the aquifer of seeping sewage (Day, 2003).

Proper management of karst waters requires monitoring and information intake of the state and functionality of the aquifer. Although there are many management problems concerning the permeability of karst aquifers, some characteristics of karst aquifers also facilitates management and monitoring.

Since most groundwater in a karst aquifer discharges from a single source on the surface, information on all of the aquifer is easily accessed. Also, the sampling types are diverse. The time frame of this paper does not allow a closer survey of these, but some will shortly be mentioned.

Tracer tests have been mentioned before and are used to determine the flowpath of waters. *Spring Hydrographs* shows how quick or slow an aquifer responds to storm inputs. This sampling test has the storm function at the swallet as input function and the output function is the hydrograph at the output point, i.e. the spring. *Spring water chemistry* can be measured, since water hardness fluctuates and responds to storm inputs. Since grounwaters in karst have much in common with surface waters elsewhere *water budgets* for karst can be written in the same way as they are done for surface water basins – something that is not possible in other types of aquifers. In a water budget, inpputs and outputs are balanced to gain knowledge about water supplies (White, 2002).

5 Discussion

There has been great progress in the area of modelling of the evolution of karst aquifers through different stages of the dissolution process, and therefore a better understanding for the constantly changing system has been gained. However, for the development of matters of practical hydrology, such as issues concerning insufficient water supplies and waste-disposal, these models are not of direct value since the problems must be viewed and resolved in present time and state of the aquifer (White, 2002).

One substantial problem concerning karst is its high permeability which results in a high probability of leakage. Leakages lead to high risks of water contamination since filtration of waters in karst often is scarce.

The effects of leakage in karst aquifers led Quinlan (1989) to propose that waste-disposal facilities shouldn't at all be placed in karstic aquifers and that hydrologists should be involved in the planning of future sites for waste-disposal. These measures should be taken in order to find the most proper sites for positioning of waste-disposal facilities and thereby minimize the risk of ground water contamination. Further Quinlan states, that if a waste-disposal facility is placed on karst terrain, at least parts of the aquifer will then not be proper for use as potable water, and that this needs to be taken into account.

The planning of waste-disposal positioning thus becomes a matter of weighting of pros and cons. The question that arises is if it is affordable to shut off parts of a water supply in order to place a waste-disposal facility at a certain site. Since water scarcity, together with leakage and water pollution, is another major problem in karst, waste-disposal facilities on karst terrains does not seem affordable from the viewpoint of water management. Subtraction from one problem and addition to another problem is not a sufficient solution in well managed systems, and should in my opinion be avoided to the furthest.

Karst waters need to be protected both legislatively and technically in order to minimize the risk of contamination and pollution of the waters. The technical precautions needed to minimize the risk of pollution in large-scale water supplies can be exemplified by one study of karst in Iran. Technical precautions are recomended on three different levels, dividing them into three protection zones (Afrasiaban, 2006). The first zone is geographically limited to the area around the immediate point of water withdrawal, and is completely restricted for antropogenic activities. The second zone's boundaries were in this study defined and set through points with distances needed for a fifty-days delay of a water particle in the aquifer. Anthropogenic activities are here somewhat less restricted than in the first area, while they are mostly conditional in the third area. The third area is defined as the catchment area of the water source, and it mainly protects quantitative and chemical properties of the water.

This type of protection of karst aquifers are not complicated and difficult to realize in any area of karst, but it reduces the problems relating water pollution, and in a higher degree ensures quality drinking water for the population that receive its water from these areas.

In order for these kind of technicalities to be realized they need to be supported by law stipulations. Laws on principles of water resources conservations and protection need to be developed if not yet existing. In addition to these, other complementing regulations should be developed. In the article by Afrasiabian (2006) such regulations are proposed to be; guidelines for water control authorities, protective zones and catalogues listing hazardous substances should be introduced and/or further developed.

The lack of surface streams in karst, and instead the presence of few or single large discharge points of water is a relation that could, if not managed properly, lead to conflicts of competition of different interests. Anew, proper legal actions and restrictions concerned with protection of the aquifers could be openings towards better and easier management of karst aquifers.

In line with what Quinlan (1989) proposes, I think that a broader incorporation of professionals from the field of hydrology should be involved in decision-making and planning of different anthropogenic activities in various aquifers, and especially in highly brittle systems such as karstic landscapes.

The major problem of karst is in my opinion still today unsufficient knowledge about the specific properties of karst that one is handling with when dealing with this type of aquifers.

The properties of karst provide multiple sample possibilities and makes information about the aquifer easily accessed. If models for practical hydrological problems would be further developed, using these sample possibilities, the problems of water scarcity and location of available water would be substantially reduced. Today these problems are widespread because techniques used and developed in other aquifers aren't readily applicable on karst aquifers. Techniques specifically developed for karst are needed in order to obtain substainable water environments.

Unsufficient monitoring and investigations of sites are also a problem of major concern. An example of this is the deep tunnels construction in Milwaukee presented in section *3.4 Problems and Possibilities of Water Management in Karst.* The area in which the tunnels were placed is mantled of impermeable rocks and there are no surface landforms to indicate karst subsurface characteristics. If studied more thoroughly, this could maybe have been known, and costs and other concerns with the project would have been avoided. Karst landscapes are heterogenous and must be considered individually and by monitoring, the aquifer can be characterized and from there proper measures of monitoring can be taken.

6 Conclusions

Karst has in many previous works been shown to be a complex system of water flow and it is critical that a better understanding of the karst aquifer is developed in order to better manage the karst aquifers, thus both preventing the occurrence of problems that could arise in karst aquifers but also making use of the possibilities that karst aquifers possess. In this literature study I have tried to compile information about karst in general and of karst hydrology in particular in an attempt to better understand and elucidate this interesting and engaging subject.

The purpose of the study was in parts (A) to map out the karst areas of the world, (B) to describe the properties of karst and karst hydrology, and (C) to define problems and possibilities of water management in karst landscapes.

Areas of karst are well distributed over the whole globe and often coincide with limestone areas of the world. The maybe most well known and also well studied areas of karst are those of Slovenia, Croatia and Serbia. These areas – through scientists that have been working in them –, that all have languages of south-Slavic origin, have given names for most occurrences used in karst terminology. Large parts of North America are also karstic terrains, as well as areas of Australia, southern China and parts of south-east Asia to mention a few.

Areas of well-developed karst are often areas of well developed subsurface formations such as caves as well, since they are characteristic features of karst.

It however has been shown that not all areas of limestone are suitable for the development of karst. One such area is constituted by large parts of northern Africa. Large areas in North Africa are limestone areas, but in the same karst is not present. This comes from the unsuitable environmental conditions for formation of karst since water needs to be present at the site for at least some periods of the year in order for karst to develop.

Karst is developed through corrosive actions on mainly carbonate rocks. Other rocks where karst can develop, but much more seldom do, are soluble rocks such as dolomite, gypsum and sand.

Water and its drainage sculptures the landscapes of karst in different way creating both surface and subsurface formations that are characteristic for karst. The surface characteristics of karst are roughly divided into *karren, karst valleys* and *karst depressions*. Features created underground are *caves* and other cavities that often result in water discharging in *springs* at the surface.

Water movement in karst is somewhat different from water movement in most other soils. The properties of a karst aquifer, characterized by the open conduits that constitute them, allows water to flow through low resistance pathways and creating its own new pathways for movement in the high permeable rocks. Thus water movement in a karts aquifer is often rapid, turbulent and more irregular in its occurrence compared to other aquifers and in many ways thus resemble surface water flow.

Since karst aquifers have been used in the same way as other aquifers in the past, some practical problems specific for karst have been evident. These have amongst other things been ground subsidence, leakage of reservoirs at the surface and leakage from and unsuitability of waste-disposal sites. The perhaps most prominent difficulty in karst areas has been the often hard-predictable water supplies and the often shortage of the same. This, together with the specific properties of karst that makes the existing water supplies highly centralized, makes karst aquifers challangeing sites to manage.

The often occuring problems of today's management of karst aquifers is the poor understanding of the specific properties of the area. Models and techniques used in other types of aquifers are not readily applicable in karst aquifers.

A conceptual model for the ever changing system of karst has thus been gained, but practical problems still needs to be solved in the present time and state of the aquifer. In order for this to be achieved both legaslative and technical protection of karst areas is needed, and cooperation between and interconnectivity of different areas of interest is as well needed.

With fresh waters being increasingly accentuated for their importance in global development and sustainability the goal of development of knowledge, understanding and actual management of the world's waters needs to be reached as soon as possible.

By a higher degree of proper management, which can only come from greater knowledge and better understanding of often complex systems in nature, movements towards decreasing water scarcity in the world and acces of safe drinking water to the whole global populations are made.

Finally, it needs to be mentioned that the scope of this paper has delimited the amount of material used in this study, and thus also the existing amount of theories, findings and points of views that could possibly have provided other usuable aspects to this study. A more extensive study on the subject could delimit this issue, and give a fuller description of it. Concluded from this study, such a thesis would be both interesting and useful – in particular in the development of practical hydrologic models that would describe, and facilitate management of water existing in the present state and time of it.

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Glossary

atmosphere – [(Greek) atmos, *vapor* + sphaira, *sphere*] the gaseous envelope surrounding the earth, that contain and transport air and water in vapour or in condensed form.

biosphere – [(Greek) bios, *life* + sphaira, *sphere*] the part of the earth and atmosphere that is capable of supporting life, i.e. where living organisms exist.

diagenesis – [(Greek) dia, *through, across* + genesis, *origination*] the process by which sediments are changed, chemically and physically, during their conversion to rocks.

hydrosphere – [(Greek) hydro, *water* + sphaira, *sphere*] the part of the earth containing water in liquid or solid form.

laminar flow – [(Latin) lamina, *layer*] regular, continuous, smooth movement of a fluid. Nonturbulent flow.

lithology – [(Greek) lithos, *stone* + logos, *word*] the physical characteristics of a rock that determine the rock type.

lithosphere – [(Greek) lithos, *stone* + sphaira, *sphere*] the part of the earth's crust that contain solid rocks.

polymorph – [(Greek) polys, *many* + morphē, *form*] the in chemistry used term for a specific crystalline form of a compound that can crystallize in many different forms.

speleothem – [(Greek) *cave deposit*] the general term for all mineral cave deposits.

stalactite – [(Greek) stalaktos, *dropping*] the term used for a speleothem hanging from a cave roof and formed by dripping water.

stalagmite – [(Greek) stalagmos, *a dropping*] the term used for a speleothem formed by upward growth from a cave floor. Complement of stalactite.

turbulent flow – [(Latin) turbidus, *disordered*] movement of a fluid that has randomly fluctuating local velocities and pressures.

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