

ATRAPANIEBLAS

– Fog as a Drinking Water Resource –



Project Work

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– Fog as a Drinking Water Resource –



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Declaration

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Hamburg, den 6.5.2010

Moritz Scharnke

Abstract

Atrapanieblas provide a technique for the collection of water out of fog. Atrapanieblas consist of a raschel mesh which is suspended vertically between two posts. The mesh intercepts the fog droplets as the fog is pushed through the mesh by wind. The water dripping down the mesh is collected in a drip rail which runs along the base of the mesh.

The technique of collecting the water vapor out of the atmosphere is well known in nature, and also humans have been using techniques for the collection of water out of the atmosphere in the arid regions of the Mediterranean since the Bronze Age. The first investigations on atrapanieblas, which are a modern, low-tech method for gaining water out of fog, started in the 1950s.

Atrapanieblas can be an efficient water source in regions with high frequencies of fog events. Good conditions can be found in low latitudes throughout the world. A warm climate is favorable for fogwater collection, as it leads to a higher liquid water content in the fog. Especially along the coasts of the arid regions in West Africa and western North and South America a high frequency of advection fog events can be observed. These thick fogs are caused by the upwelling of cold ocean currents, and trade inversions which are also the cause for the scarce rainfall in these regions. Orographic fog occurring in mountainous regions is also reliable for fogharvesting with atrapanieblas. In months with a high frequency of fog events, the collected water can be over 30 l/m²/day.

Through analyses of fogwater collected in Alto Patache, Chile, it was found out that this water is acidic (pH 3.3) with high concentrations of the trace metals iron, lead, arsenic, and selenium. Among the factors causing this poor water quality are the special chemical properties of fog droplets, the influence of dimethylsulfide generated in the ocean, anthropogenic influences, and the deposition of dust in the mesh of the atrapanieblas.

Experiments with fogwater collected in Alto Patache and CaCO₃ showed that an increase of the pH above 6.5 and a reduction of arsenic below the *WHO* guideline value of 10 µg/l is possible by mixing CaCO₃ in powder form with the water with poor quality. As the constant mixing of powdery CaCO₃ with the water in a large-scale on site is not feasible, the use of a multilayer filter with a layer of limestone in granular form is recommended.

Kurzfassung

Atrapanieblas stellen eine Technik dar, um Wasser aus Nebel zu gewinnen. Atrapanieblas bestehen aus einem Raschelnetz, welches vertikal zwischen zwei Pfosten aufgespannt ist. Das Netz fängt die Nebeltropfen auf, die mit dem Wind durch das Netz transportiert werden. Das Wasser tropft am Netz ab und wird von einer Regenrinne aufgefangen, die entlang der Unterkante des Netzes verläuft.

Die Methode den Wasserdampf aus der Atmosphäre zu sammeln ist in der Natur weit verbreitet, und auch Menschen haben verschiedene Techniken zur Gewinnung von Wasser aus der Atmosphäre in den ariden Zonen rund ums Mittelmeer seit der

Bronzezeit angewandt. Die ersten Untersuchungen zu Atrapanieblas, welche eine moderne low-tech Methode zur Gewinnung von Wasser aus Nebel darstellen, wurden in den 1950er Jahren durchgeführt.

Atrapanieblas können eine ergiebige Wasserquelle in Regionen darstellen, die ein hohes Aufkommen an Nebelereignissen haben. Gute Bedingungen sind weltweit in niederen Breiten anzufinden. Ein warmes Klima begünstigt das Einfangen von Nebelwasser, da es zu einem höheren Wassergehalt im Nebel führt. Besonders die Küsten in den ariden Zonen von Westafrika und dem westlichen Nord- und Südamerika haben ein häufiges Vorkommen an Advektionsnebel. Diese dichten Nebel werden durch das Hinaufströmen von kalten Meeresströmungen an die Wasseroberfläche und durch Passatinversionen erzeugt. Passatinversionen sind auch der Grund für die geringen Niederschläge in diesen Regionen. Orographischer Nebel tritt in bergigen Gebieten auf und bietet auch eine verlässliche Nebelwasserquelle für Atrapanieblas. In Monaten mit einem hohen Aufkommen an Nebel kann die Wasserausbeute über 30 l/m²/Tag betragen.

Wasseranalysen, die an Nebelwasser durchgeführt wurden, welches in Alto Patache, Chile, gesammelt wurde, haben ergeben, dass dieses Wasser sauer ist (pH 3.3) und hohe Konzentrationen von den Schwermetallen Eisen, Blei, Arsen und Selen hat. Zu den Faktoren, die verantwortlich für diese schlechte Wasserqualität sind, gehören die chemischen Eigenschaften von Nebeltropfen, der Einfluss von Dimethylsulfid, welches in Ozeanen erzeugt wird, anthropogene Einflüsse und die Ablagerungen von Staub in den Netzen der Atrapanieblas.

Experimente, die mit Nebelwasser aus Alto Patache und CaCO₃ durchgeführt wurden, haben gezeigt, dass eine Anhebung des pH-Wertes über 6,5 und eine Reduktion der Arsenkonzentration unter den WHO Richtwert von 10 µg/l durch das Zumischen von pulverförmigem CaCO₃ möglich ist. Da die kontinuierliche Zugabe von pulverförmigem CaCO₃ im großen Maßstab vor Ort nicht praktikabel ist, wird die Verwendung von Mehrschichtfiltern empfohlen, die eine Schicht Kalksteingranulat beinhalten.

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List of Acronyms and Abbreviations

ASRC	Atmospheric Science Research Center
DMS	dimethylsulfide
LFC	Large Fog Collector
SFC	Standardized Fog Collectors
TWDB	Texas Water Development Board
UNDP	United Nations Development Programme
WHO	World Health Organization

List of Chemical Formulas

Al^{3+}	aluminum
Al_2O_3	aluminum oxide
As^{3+}	arsenite
As^{5+}	arsenate
CO_2	carbon dioxide
CO_3^{2-}	carbonate
Ca^{2+}	calcium
CaCO_3	calcium carbonate
CaO	calcium oxide
Ca(OH)_2	calcium hydroxide
$\text{CaMg(CO}_3)_2$	dolomite
$\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$	gypsum
Cd	cadmium
Cl^-	chlorine
Cr	chromium
Cu	copper
F^-	fluoride
Fe	iron
Fe^{3+}	ferric
Fe_2O_3	iron oxide
Fe(OH)_3	iron hydroxide
H^+	hydrogen
HCO_3^-	hydrogen carbonate

H ₂ O	water
H ₂ SO ₄	sulfuric acid
K ⁺	potassium
Mg ²⁺	magnesium
Mn	manganese
NH ₄ ⁺	ammonia
NO	nitric oxide
NO ₂	nitrogen dioxide
NO ₃ ⁻	nitrate
NO _x	NO and NO ₂
Na ⁺	sodium
Na ₂ CO ₃	sodium carbonate
NaOH	sodium hydroxide
Ni	nickel
NSS-SO ₄ ²⁻	non-sea-salt sulfates
PO ₄ ³⁻	phosphate
Pb	lead
SO ₂	sulfur dioxide
SO ₄ ²⁻	sulfate
Se	selenium
Zn	zinc

1 Introduction

Water shortage is a serious problem in arid and semiarid climates around the world. Also remote villages can have an insufficient water supply due to their location. Often the local population has to undergo tremendous efforts to fetch water for the everyday use from a nearby spring or well. Very long marches or dangerous, difficult to use paths are not uncommon. The contamination of local water sources, such as rivers or lakes, is increasing the problem of providing the resident population with local safe drinking water sources. Sometimes the only supply of drinking water for villages exists in the regular visit of water trucks. But some of these regions with low or no rainfall have regular fog events. It is possible to collect water out of fog by intercepting the fog droplets with large nets. These structures are called *atrapanieblas* (Spanish, meaning “trapping fog”) and mainly consist of a large net suspended vertically between two posts. Thus they present a low-tech water source, which can be built and maintained by the local population. *Atrapanieblas* can be built locally for remote villages, where the climatic conditions permit this, and provide these villages with their own drinking water source. In villages with a formerly inadequate water supply this new water source can raise the per capita supply of drinking water. This improves the living conditions by providing enough water for personal consumption and hygiene, thus leading to a healthier life of the inhabitants.

Unfortunately, in some regions the fogwater has low pH and high concentrations of trace metals and has to be treated prior to consumption. This is also the case in Alto Patache, a research area in northern Chile of the *Centro del Desierto de Atacama*, which does research on the desert environment and the use of *atrapanieblas*. As *atrapanieblas* present a feasible alternative to traditional water sources, and as some arid regions have a high frequency of fog events, it is important to do further research on this technique and to improve it further. One area of improvement is the development of a low-tech water treatment system which can be built and maintained by the local population with local materials. The objective of this paper is to introduce the concept of *atrapanieblas*, as it is still widely unknown throughout the world, and to offer first suggestions and solutions for a low-tech treatment system. This research is based on the water analyses done by *Sträter* in Alto Patache in 2009. In addition, own experiments with water treatment were conducted on water collected in Alto Patache.

The first chapter explains the concept of *atrapanieblas*. The chapter gives examples of the use of fog and dew in nature by plants and insects to improve their water supply. Also some ancient human methods to collect water out of the atmosphere, dating back to the Bronze Age, are introduced. To understand the concept of collecting water out of the atmosphere better, a short explanation of fog and dew, and of the conditions which lead to fog formation, is given. The design of *atrapanieblas*, as it has proven itself in numerous projects, is explained in detail and what environmental requirements are necessary for the use of *atrapanieblas*. In this context, global and local climatic systems that provide favorable environments for the use of *atrapanieblas* are explained, and the major locations throughout the world, where these environments are found, are named.

The second chapter is about the quality of the water collected in Alto Patache. Possible origins of the water quality are discussed and the degree of pollution is explained by comparing the chemical constituents of the fogwater with the guideline

values of the *WHO*. Also the negative health effects of the constituents, whose concentrations exceed the guideline values, are explained.

The third chapter explains low-tech treatment methods for raising the pH and lowering the arsenic concentration. To study on these low-tech methods, fogwater collected in Alto Patache was treated with calcium carbonate (CaCO_3). This experiment and its results are discussed, as well as how CaCO_3 can be applied in a treatment system.

2 Fog Collectors

This chapter is about natural and man-made fog collectors. To begin with, fog and dew are explained and the conditions under which they form. The chapter then describes the capability of plants to collect water out of fog and dew, and the history of techniques used by humans to collect water out of fog and dew for themselves. In this context, the concept of *atrapanieblas* is explained. These are fog collectors used today in regions with low water supplies but regular fog events. Furthermore, the climatic requirements are explained under which fog suitable for fog collection forms, and where these environments can be found on a global scale.

2.1 Fog and Dew

The formation of fog and dew in nature is explained in this chapter. *Häckel* (2008) and *Liljequist and Cehak* (1984) give descriptions of fog and its formation. Dew is described by the *Meteorological Office* (1991) in its *Meteorological Glossary*. The following explanation is based on their descriptions.

2.1.1 Fog

Fog is the condensation of the water present in the atmosphere. The water in the atmosphere is present in gaseous form as water vapor. Its amount in the atmosphere is defined as humidity. If the atmosphere is supersaturated of water, the water vapor condensates on aerosols, the condensation nuclei, and water droplets of microscopic scale form. These droplets can be less than 10 μm and up to 100 μm in diameter, whereas larger droplets deposit to the ground by gravity faster than smaller droplets. Transported by winds the droplets can be in suspension in the air. Any fog event shows a wide spectrum of droplet sizes. The moisture of the fog depends on the size of its droplets. The larger they are, the more distinctive is the characteristic of fog to moisten surfaces upon contact. Fog which consists of droplets with diameters of 5 to 10 μm or less has no or only light moistening capacity. Droplets with a diameter of 20 to 40 μm produce fog with high moistening capacity. The liquid water content of fog ranges from 0.01 to 0.30 g water per m^3 , with the most liquid water content to be found in droplets with diameters 10 – 30 μm (*Hoag et al.* 1999). The movement of fog is dependent on air movement. The diameter of droplets, which are intercepted the most by the mesh of fog collectors, are between 10 and 16 μm (*Schemenauer and Joe* 1989).

There are different types of fog with different characteristics, depending on how it was formed. Radiation fog is formed when the ground cools down significantly due to strong radiation loss and the lower air layers transmit their heat through radiation to the ground causing the air to cool down. If the air is cooled down below their dew point, condensation begins and radiation fog forms. This process normally takes place when there are high temperature differences between night and day, and when the lower air layer is humid. The droplets of radiation fog are very small and therefore radiation fog is not, or only slightly, moistening. Radiation fog dissipates easily under solar radiation.

Advection fog is generated when warm, humid air flows over a cold surface or air layer. This is the case when the sea or a large inland lake is colder than the adjacent landmasses and warm air from the land flows over it, cooling down in the process. Warm air can also be transported by wind currents to colder regions where it may flow over colder air layers near to the ground. Advection fog also forms where warm

and cold ocean currents collide or where cold deepwater emerges to the surface. This is the case at the Pacific coasts of North and South America and the Atlantic coasts of Africa. Typical advection fog in the bay of San Francisco, California, is depicted in figure 1. Advection fog is very rich and persistent and can only be cleared by exchange of air masses. The fog can be moved onshore by winds and, due to winds and turbulences, it can lift off the surface and turn into stratiform clouds.



Fig. 1: Advection fog in San Francisco (Robert Cameron)

The third category is orographic fog which forms when warm, humid air flows up a mountain slope where it cools down. This is causing the water in the air to condensate as fog when the condensation level is reached, at which point the cooling air becomes saturated with water. If the condensation level is low, fog will be generated after minor elevation of the air masses. If the condensation level lies above the mountaintop, clouds are generated.

A mixture of advection and orographic fog is possible.

Though both advection fog and orographic fog are rich in water droplets it showed that advection fog has a higher liquid water content than orographic fog. On the other hand, concentrations of chemicals tend to be higher in orographic fog than in advection fog. This was observed by *Sträter* (2009) who conducted analyses of water collected by *atrapanieblas* in Alto Patache, Chile.

Chapter 3 will go into further detail of the water quality of fogwater and the water collected by *atrapanieblas* in Alto Patache, Chile. The chemical properties of fog droplets are explained in chapter 3.2.1.

2.1.2 Dew

Dew forms when water vapor condenses on a colder surface that is cooled down by radiation at night. The formation of dew can proceed in two different processes. One occurs when water vapor, which is diffusing upwards from the soil, condenses on surfaces close to the ground, for example grass. This process proceeds under calm

conditions with no or little wind. The other process occurs when the water vapor in the atmosphere is transported down to the colder surfaces by winds. The highest dewfall rates occur when there is a clear sky at night, high air humidity and some wind.

2.1.3 Definition of Condensation

As condensation is also part of the process where cloud and fog droplets form on aerosols, the term condensation is scientifically used in all processes related to the formation of water droplets out of the water vapor present in the air. In order to clarify whether the droplets form in mid-air on aerosols or on surfaces, it is always stated when the condensation happens on surfaces. The term precipitation is used when both processes take place.

2.2 Fog and Dew Collection in Nature

The procedure of extracting water from fog and dew is a widespread method in nature for gaining water. Plants and insects use this water resource for their daily water consumption. Large ecosystems dependent on fogwater are tropical cloud forests, the coastal redwood forests in California, and ancient forests in semiarid climates and deserts.

In tropical cloud forests the vegetation canopy has a significant effect on local precipitation. Figure 2 shows the distribution of cloud forests worldwide and the figures A1-A3 in the appendix A show the locations more detailed per continent. These forests are frequently enclosed by clouds or fog. *Tiedemann* (2001) studied the fog-combing ability of leaves and the water balance of tropical cloud forests. The leaves intercept the fog and cloud droplets, which then drip off the leaf surfaces towards the ground. This process is known as horizontal precipitation. The tree roots and understory vegetation then take the water up. Long, thin, firm leaves with small surface areas each, which are arranged lattice-like with enough permeability for wind, are most suitable for combing water out of the fog. According to *Murugan et al.* (2009) the horizontal precipitation in cloud forests around the world is up to 14 – 18% of the total precipitation in wet seasons and 15 – 100% in dry seasons.



Fig. 2: Worldwide distribution of cloud forests (Malene Thyssen)

The coastal redwood forests along the western coast of the USA are another good example for natural fog collection. These trees can grow over 35 m high and their leaves are needle-like, growing in alternate arrangement and moderate density (*Gilman and Watson 1994*). During the summer (June – November), which has the least rainfall in the year, the redwood trees gain 8 – 34% of their water consumption through horizontal precipitation. The water consumed by the understory vegetation is even up to 100% precipitated out of fog during that period (*Dawson 1996*).

Forests that gain a large part of their water consumption through horizontal precipitation can also be found in semiarid climate zones. The forest in the national park Fray Jorge, introduced on www.conaf.cl, in Chile is one example. It lies in a semiarid climate on the southern border of the Atacama Desert, one of the driest deserts in the world. The ancient forest, more than 30,000 years old, lies on a mountain ridge running along the coast. The average annual rainfall in this location is only 113 mm, but in the forest the average annual precipitation is about 800 – 1000 mm due to the frequent fog flowing over the mountain ridge and being combed by the trees.

At the coast of southern Oman lies the 800 – 1000 m high Jabal al Quara mountain range, which is adjoining to the world's largest sand desert, the Rub al Khali, but nevertheless has a vegetation rich in species. Apart from heavy rainfalls which only occur once in a few years the only water source is the annual wet season in summer (mid June – mid September). During this period moist air from the Indian Ocean transported by southwestern monsoons (see chapter 2.5.2.1.2) is being pushed up the mountain slopes by air currents, resulting in drizzle rain and a constant immersion of the mountain range in clouds. This allows trees, which need significantly more water than the annual rainfall of 250 mm occurring in this region, to grow there. These trees are adapted to cloud stripping, thus collecting water out of clouds, and are in leaf during the wet season (*Hildebrandt 2005*).

Once cloud forests and other forests with frequent fog precipitation are destroyed the specific climate of the region cannot sustain itself and desertification is the result. Because of the lack of trees, the fog water on which the other plants are also dependent is no longer collected. This leads to the dying off of the smaller plants as well. The change of the local climate is also a consequence. Forests have the nature of absorbing more heat radiation, and this results in a colder local climate. Forests also have a higher evapotranspiration than open land. A destruction of the cloud forests results in a warmer and dryer climate. A reduction of rainfall in areas with massive forest clearance has been observed (*Tiedemann 2001*).

Cacti and succulents of arid regions are also known for their dew collecting capabilities. Their spines and thorns collect dew water and divert it towards the body and the roots (www.cssnz.org).

Insects use the concept of gaining water out of fog and dew for their daily water consumption, as well. The Namib Desert beetle for example, described by *Summers (2005)*, has the ability of collecting water droplets out of morning fog on its body by standing on top of a sand dune in the Namibian desert with its lower body raised to intercept the moist wind. Droplets stick to its body and, when reaching a certain size, roll down towards its mouth.

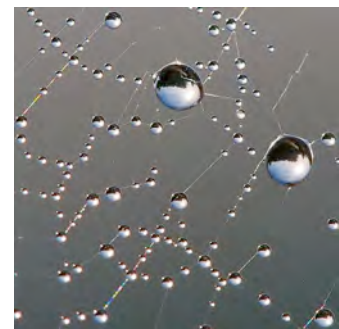


Fig. 3: Dew in spider web
(Luc Viatour)

Zheng *et al.* (2009) report that spider webs have ideal physical properties for collecting water droplets out of humid air (see figure 3), providing the spider with fresh water. The special design of the spider silk makes it very efficient in water collection.

2.3 History of Human Fog and Dew Collection

Humans have known about nature's ability to collect water out of fog for millennia and have been using this water for their own water supply. But humans were also using man-made structures for the collection of water out of the air since ancient times. A collection of these methods used in arid and semiarid regions around the world is introduced in this chapter. These were structures made out of stones in form of barrows, mounds, or walls. Also underground structures, such as foggaras, were built. Reminders of these structures can be found worldwide and some are still in use today. Furthermore air wells are introduced, which were collectors of water vapor built at the beginning of the 20th century.

2.3.1 Use of Fog Collected by Nature

Until the beginning of the 17th century, the inhabitants on the Canarian island El Hierro, the Bimbaches, were using the water collected by their sacred tree Garoé. This was a tall tree in an exposed location precipitating the water out of the clouds passing over it and thus was constantly dripping water off its leaves towards the ground. The Bimbaches took the water out of a pond underneath the tree or collected the droplets falling down to the ground with jars (Hutchinson 1919). A similar method can still be seen in the mountains in Oman, where open cisterns were built below trees for water collection, as shown in the publication of Schemenauer and Cereceda (1994a).

2.3.2 Underground Structures

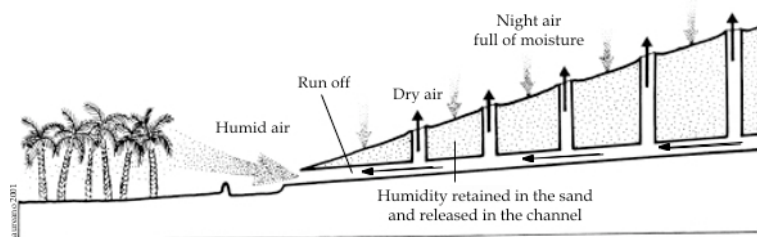


Fig. 4: Cross-section of a foggara (IPOGEA)

the horizontal tunnel with the surface, as illustrated in figure 4. These vertical canals enhance the airflow inside the tunnel. The method of foggaras is well known in North Africa and throughout the Middle East under many different names (Klaphake 1936, IPOGEA n.d.).

Foggaras are ancient tunnels in the Sahara, which collect seepage but also allow warm, moist air to enter, thus also collecting precipitated water out of the cooled down air. This effect is achieved by vertical canals, connecting

2.3.3 Stone Structures

Due to the high differences of day and night temperatures in deserts condensation of water on cold surfaces, such as rocks, in the morning is noticeable. One square meter of surface can collect 4 cm³ of water per day. The way water vapor has been collected out of the air using methods such as stone structures and other man-made structures in the Mediterranean arid zones is described by Laureano (2008) and IPOGEA (n.d.). These methods date back to the Bronze Age.

The most common structures to collect the water vapor out of the air were stone piles with a chamber inside (a cross-section of this structure can be seen in figure 5). During the day, the outside temperature would be much higher than the temperature inside the stone pile. When warm, moist air entered the stone pile and cooled down inside, water droplets were precipitating and falling down

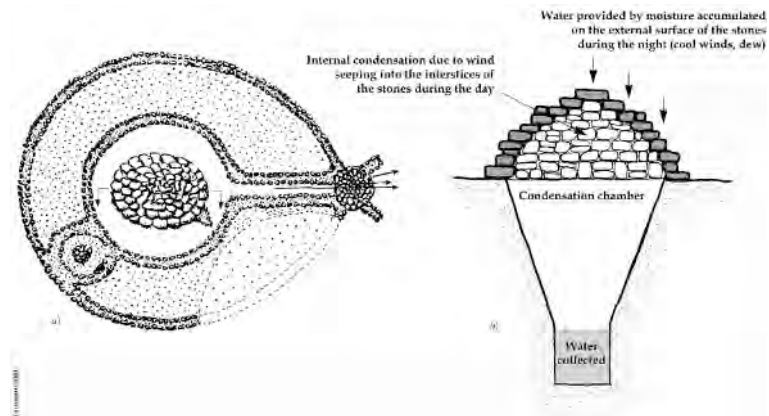


Fig. 5: Water collection with an ancient water condenser ((a) plan, b) cross section) (IPOGEA)

into the cavity underneath the stone pile. The accumulation of water underneath the stone piles also enhanced the cooling effect of the structure and raised the humidity inside. This led to a further amplification of the efficiency of the stone pile and its condensation chamber. During the night and morning the process was reversed with water condensing as dew on the outside wall of the stone pile. The water was then lead inside through interstices into the cavity. Remains of this technique can be found in the Atacama Desert (Dower 2002) and in the arid regions of the Mediterranean region, especially in Northern Africa and the Arabian Peninsula. The ancient civilizations of Greece very likely used the method of dew and fog collection as well. Remains of structures on hilltops, connected to a water system, have been found on the Crimean peninsula. These date back to ancient Greece and can very likely be dew or fog collectors (Klaphake 1936). Prinz and Wolfer (1998) also report that stone piles supposedly built for the purpose of dew collection have been found on the Crimean peninsula. On the Dahalac isles in the Red Sea underground jars with stone piles covering them are still used today for collecting and storing water (IPOGEA n.d.).

In ancient Palestine circular honeycombed walls were constructed around vines, collecting dew and mist close to the plants (Dower 2002). The technique of improving ground moisture for agriculture through water condensation on stones, investigated in detail by Lightfoot (1996), was still used in the last century in agriculture in many parts of the world. For example in North America small stonewalls around the trunks of fruit trees were widely used to improve the harvest. Another way of elevating the moisture of the ground is stone mulching. This technique is known around the world, e.g. Roman Italy, Arizona, Argentina, New Zealand, the Canarian Islands, India, and China, and is still used today. Gupta and Ashok (2007) describe how the moisture of the ground is maintained through a mixture of gravel and soil, which forms the uppermost layer of the soil. On the one hand it serves as dew collection when there is a gravel layer on top, on the other hand it minimizes



Fig. 6: Tiers of stone used for irrigation on Dahalac isles, Red Sea (IPOGEA)

evaporation losses and increases the soil temperature. The mulch also reduces soil-crust formation and thus enhances the infiltration of water.

By building tiers of stone, the villages of the Dahalac isles in the Red Sea collect water vapor out of the air and direct the water to the soil for irrigation of the fields up until today (see figure 6). Building mounds of stones, crescent shaped or in circles, has the same effect and was used in the arid regions of the Mediterranean area for the irrigation of trees and plants. The solar tombs of the Sahara desert, concentric circles around a barrow, are believed to have the same effect (*IPOGEA n.d.*).

2.3.4 Stone Structures of the 20th Century

Nelson (2003) describes structures built for dew collection at the beginning of the 20th century. A few scientists were experimenting with dew collection by building so-called air wells. These worked with the same technique as the ancient stone piles, allowing warm air to enter a cool chamber or environment, where the moisture condensed on cold surfaces. The most efficient version was a cone-shaped heap of medium-sized rocks (10-40 cm in diameter), 6 m high and 20 m in diameter, which was a replica of the old stone piles found on the Crimean peninsula. It was built on the Crimean peninsula by Friedrich Zibold in the year 1912 and collected up to 360 l/day (see figure 7). Other designs, e.g. different shaped stone chambers above ground (see figure 8), weren't nearly as efficient. A different approach to air wells was to build the condensation chamber underground, using the lower temperatures to cool the chamber.



Fig. 7: Zibold's air well (*Nelson 2003*)



Fig. 8: Knapen's air well, built in 1931 (*Nelson 2003*)

2.4 Atrapanieblas

Over the last decades the concept of collecting water out of fog again became more important as an alternate water resource. Today, this is done with fog collectors, called *atrapanieblas*, which are built in Chile and numerous other countries worldwide. The *atrapanieblas* consist of large meshes suspended vertically between posts which collect the water droplets out of the fog as the fog is passing through the meshes. The fog with its droplets is pushed through the mesh by the wind. The droplets then collide with the fibers of the mesh and stay attached to them. When the

droplets accumulate and grow, they drip down the mesh into the drip rail. Condensation, as used in the ancient methods, only has a minor influence in this method.

2.4.1 History of Atrapanieblas

Acosta Baladón (2003) gives a brief summary of the implementation of this technique. The history of investigations of possible fog harvesting sites for atrapanieblas worldwide and in Chile, with their different water yields due to different climatic conditions, is depicted in the tables 1 and 2. The first feasibility studies were undertaken in 1954 – 1955 on the Table Mountain in South Africa. The average yield over one year was 9 l/m²/day. Investigations on Tenerife in 1960, Cape Verde in 1962 and 1980, and Gran Canaria in 1965 were following. The highest yield was achieved on Serra Malagueta, Cape Verde, with an average over one year of 13.4 l/m²/day. In Chile the first investigations for good fog harvesting locations were undertaken in 1962 in Miramar. An average yield of 3 l/m²/d was achieved. In 1987 in El Tofo, Chile, the first large scale fog collection project was implemented for the fishing village Chungungo. 50 fog collectors were built, and in 1992 25 fog collectors were added. The average water yield was 3 l/m²/day providing each inhabitant with 33 l/day (*Schemenauer and Cereceda* 1994a). Since this project, the first large-scale and successful use of atrapanieblas, similar systems have been built all over the world in Guatemala, Yemen, Nepal, Namibia, Haiti, Ecuador, Peru, Ethiopia, Morocco, and Eritrea by the NGO *FogQuest* (www.fogquest.com), to provide water for villages with no other water sources. The investigation of new sites is still ongoing.

Table 1: Investigations for possible sites worldwide (in reference to Laureano 2008)

Period	Site	Specific Collection [l/m ² /day]
1954 – 1955	Table Mountain (South Africa)	9.0
1960	Izaña (Tenerife, Spain)	4.4
1962	Monte Velha (Cape Verde)	7.7
1962	Pero Dias (Cape Verde)	4.9
1962	Aguas das Caldeiras (Cape Verde)	3.8
1965	La Cumbre (Gran Canaria, Spain)	2.5
1980	Serra Malaguete (Cape Verde)	13.4

Table 2: Investigations for possible sites in Chile (in reference to Laureano 2008)

Period	Site	Specific Collection [l/m ² /day]
1962	Miramar	3.04
1962 – 1963	El Mirador Loma del Ciprés	1.01
1964	Miramar	0.66
1963 – 1964	El Mirador Estación Andrómeda	0.33
1964 – 1965		0.27
1967 – 1968		0.60
1968 / 1972	Taltal	1.40
	Michilla	2.27
	El Mirador	3.32
	Miramar	5.21
	Morro Moreno	3.04
1968 / 1972	Morro Moreno	1.48
1984	El Tofo	10.96

2.4.2 Design of Atrapanieblas

In this chapter the design of the Large Fog Collector (LFC) is explained. The presented design has proven itself in numerous projects in Chile and around the world. The design is explained in detail by *Schemenauer and Joe* (1989), *Schemenauer and Cereceda* (1994b), *Giodai et al.* (1993), and *Apigian* (2005). It was also possible to study the design first-hand in personal visits to the two sites Peña Blanca and Alto Patache in Chile.

2.4.2.1 LFC

The LFC consists of a double layer of raschel mesh which is suspended vertically between two posts (see figure 9). Underneath, along the base runs a drip rail (see figure 10) to collect the fogwater which drips down the mesh after it came in contact with the mesh.



Fig. 9: Atrapaniebla in Alto Patache



Fig. 10: Drip Rail of Atrapaniebla in Alto Patache

The dimensions of the mesh are usually 12 m wide and 4 m high but can differ slightly. Thus the area of one fog collector is 48 m². The mesh is hanging between the two posts so that the base of the mesh is between 1 and 2 m above the ground. An array of several meshes using joint posts between them is possible. This reduces the number of posts needed when a larger mesh area is required. If the meshes themselves are larger, higher forces are needed to tauten the mesh. In recent projects the atrapanieblas are built manually without machines, and a good tension of the mesh involves considerable effort. Making the mesh larger therefore results in much higher effort for the construction of one atrapaniebla. Underneath the base runs a drip rail which collects the condensed water dripping down and off the net. The diameter of droplets that are intercepted the best by the mesh of fog collectors is between 10 and 16 μm .

The material of the mesh usually is raschel mesh, made out of polypropylene with a shade coefficient of 35% (see figure 11). The shade coefficient is a parameter that indicates how much direct sunlight will be blocked from passing through the mesh (www.gemplers.com). Raschel mesh is widely used in agriculture for shading purposes and therefore is resistant against UV radiation and inexpensive. The mesh consists of a weave made out of a flat fiber (approximately 1 mm wide). The fibers are woven in between horizontal support fibers in long, triangular arrangement, allowing a vertical water flow. For the LFC the mesh is used as a double layer with the layers touching each other. This results in a coverage of the mesh area by fiber of about 60%.

It is very important that the suspended mesh is very taut. If this is not the case the mesh will bulge in the wind, and part of the condensed water won't drain off into the drip rail running along the lower base of the mesh, but drip off beside it to the ground. The tension of the mesh is attained by running cables along all four edges of the mesh and joining them at the four corners of the mesh. The top corners are fixed to the top of the posts by short cables. Here it is important to span the top cable and with it the top edge of the mesh as tense as possible. The bottom two mesh corners are connected downwards to the posts. The connecting cables have cable fasteners to tighten the cables and increase the tension of the mesh. Further stability is achieved if the horizontal cables are not connected to the posts but run on towards anchors in the ground. The top cables run over, beside, or through the posts and the bottom ones run beside or through the posts. These cables are anchored in a slant way to the ground giving higher stability to the structure as not all the horizontal forces of the tense mesh are transferred to the posts.

The posts are generally made of wood which is treated against corrosion. The posts have a length of about 6 to 7 m and are buried about 1 m deep into the ground to enhance stabilization. The posts are securely anchored to the ground with several steel cables so that they can take up the tensions of the mesh. The steel cables run from the top of the posts in three directions towards the ground, where they are anchored with submerged anchor blocks. The anchor blocks consist of concrete or large boulders. The cables can also be tightened using cable fasteners. A tensing cable runs between the tops of the posts. This cable gives the structure more rigidity during strong winds. Figures 9 and 10 show a functioning atrapaniebla.

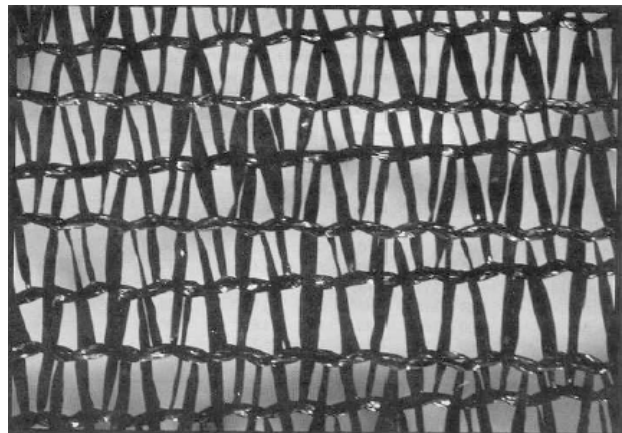


Fig. 11: Raschel mesh (Schemenauer and Cereceda 1994b)

It is important that the water flow in and from the mesh does not get into contact with iron, so that the iron is not weakened by corrosion and the iron concentration in the water cannot be increased. For this reason all steel cables touching the mesh have to be encased in plastic tubing and the drip rail and its fixture have to be made out of plastic as well.

The collected water in the drip rail is piped through PVC-pipes by gravity to nearby water tanks for storage.

In the center of the mesh of an LFC the collection efficiency is about 66%. The whole atrapaniebla with a double layer of raschel mesh has a collection efficiency of 20%. The collection efficiency indicates how much of the total water present in a fog as fog droplets can be collected by the atrapaniebla.

Atrapanieblas can also collect rain and drizzle (www.fogquest.com).

2.4.2.2 Different Mesh Materials

Besides the raschel mesh, which is easily available in South America and has very good water collection capacity, other materials have been tested. This was mainly the case in countries where raschel mesh is difficult or impossible to get. In Jordan, local sacking material delivered a good yield of fog water (*Al-Jayyousi and Mohsen*

1999). In Namibia indoor Aluminet greenhouse shade nets with a 40% shade coefficient were the most efficient during the testing of different local mesh materials (*Shanyengana* 2003). It is important for a potential mesh to have vertical fibers, which lead the droplets downwards into the drip rail. The ideal properties of the mesh for a maximum yield of fogwater have not been researched in detail so far.

It was observed by *Schemenauer and Cereceda* (1994b) that, if the mesh is dense with a very high coverage area of the fibers, the wind flow is obstructed. The result is, that the wind and with it the fog droplets will flow around the mesh instead of through it. A low yield of water is the consequence.

2.4.2.3 Maintenance

A regular maintenance of the atrapanieblas is necessary. The mesh will wear off after a few years, especially if cables touch the surface of the mesh. This should be avoided to reduce the risk of fraying the mesh due to constant friction between cable and mesh during stronger winds. Rips should be repaired immediately, otherwise the whole mesh can tear. A complete replacement of the net is mandatory after a few years. The lifespan of a mesh varies from region to region with the different climates. In regions with strong winds the damage of the mesh or even the destruction of the whole fog collector is more likely (*Makuti et al.* 2004).

2.4.3 Investigation of New Sites

2.4.3.1 SFC

Before setting up an LFC the local conditions have to be studied. The fog intensity can vary locally thus a feasibility study is necessary. Setting up Standardized Fog Collectors (SFC), as explained by *Schemenauer and Cereceda* (1994b), is a vital part in the investigation of a new site. The SFC is used for the measurement of the water yield at a specific location. It is a square mesh with an area of 1 m². The water yield per square meter collected by an atrapaniebla at that location can be very easily measured with the SFC.

The SFC consists of a frame with a double layer of raschel mesh. The frame has the dimensions 1 x 1 m and the base is at a height of 2 m. It is supported by two metal posts standing on either side. The posts have small concrete foundations and are further stabilized by wires running from the top. This design is shown in figure 12. The frame can also be put up by using a single post. However, this makes it more likely for the frame to turn in the wind and for the mesh to touch the post. This has to be prevented as this will alter the results. There are also other designs used for collecting fog water, for example the design of the ASRC (Atmospheric Science Research Center, State University of New York) (*Falconer and Falconer* 1980). This collector consists of vertical strings arranged in a circle. But it is mainly used for collecting fog water for water analyses and does not have the exact same characteristics of an SFC and LFC respectively.

2.4.3.2 Conditions for Successful Fog Collection

To define a site's capacity of generating fog for fog collection and its reliability the following factors are important to know: fog water yield (l/m²/day), wind speed (m/s), general wind direction, water quality, and rainfall (mm/day).

The fog water yield may vary between locations at the same site due to different topographic conditions which influence wind speeds, the flow of the fog or clouds, and/or the formation of different kinds of fog (radiation fog, advection fog, orographic fog).



Fig. 12: Two SFC in Alto Patache

The wind speed has an effect on the water collecting ability of an *atrapaniebla*. *Schemenauer and Joe* (1989) did research on this topic. Higher wind speeds can result in a lower yield of water. The range of droplets with diameters of 10 μm to 16 μm is the droplet size most intercepted by the mesh fibers. The collection of droplets with a diameter of 11 μm is affected very little by different wind speeds ranging from 3.5 to 6.5 m/s. Whereas droplets with a diameter of 15 μm are more likely to be collected in higher wind speeds (this was measured in wind speeds ranging from 1.9 to 3.4 m/s). In general, a better collection efficiency is achieved with larger droplets and at higher wind speeds (*Schemenauer and Cereceda* 1994b). In eastern Spain the maximum collection rate was achieved at wind speeds of 15 km/h, respectively 4.2 m/s. Here it was observed by *Estrela et al.* (2004) that the collection rate decreases under higher wind speeds. An explanation for this could be that, if the wind is too strong, droplets will be pulled off the fibers again, causing them to drop off beside the drip rail to the ground. This was observed in Alto Patache where plants grow underneath the *atrapaniebla* using the water not collected by the drip rail, as can be seen in figure 13.



Fig. 13: Plants growing underneath an atrapaniebla due to water dripping beside the drip rail

However, these measurements by *Estrela et al.* (2004) were conducted using a string collector based on a design of the ASRC (Atmospheric Science Research Center, State University of New York) (*Falconer and Falconer* 1980). As mentioned above, this collector does not have the exact same characteristics of an SFC or LFC. Nevertheless, the results of *Estrela et al.* (2004) can be compared to some extent with the collection abilities of LFCs.

As mentioned before, in regions with regular strong winds atrapanieblas can be destroyed by the wind forces. An alteration of the design has to be considered if strong winds occur regularly at a new site.

In order to differentiate water collected by atrapanieblas from fog and from rainfall, the rainfall has to be measured separately. The general wind direction is also important to know, as atrapanieblas consist of a flat surface, whose alignment cannot be changed once set up. To achieve a high yield throughout the year the atrapaniebla has to be aligned facing the general wind direction with its surface (*Apigian* 2005).

The ideal location for an atrapaniebla is on top of ridges close to the windward slope, or on the upper part of the windward slope. This ensures a good interception of the fog. However, the wind speeds should not be too high.

The water quality of the collected water can also alter from site to site. It can, amongst other reasons, be influenced by local industry and deposition of soil in the nets. These can have negative effects on the quality of the water collected by atrapanieblas. Chapter 3.2 discusses the influence of anthropogenic and natural contamination sources on the water quality of atrapanieblas in more detail.

2.5 Climatic Requirements

In this chapter, the local and global climatic requirements for the use of atrapanieblas, and where these occur, are explained. Since radiation fog has almost no moistening capacity, the presence of advection fog, orographic fog, or a mixture of both is relevant at a site for possible fog collection. These kinds of fog are also more persistent than radiation fog. Advection fog forms regularly over cold ocean currents and due to trade inversions. Orographic fog can form regularly due to trade winds or stable, local mountain winds. As wind is a crucial factor in the creation of fog at mountains, the transportation of fog towards land, and the fogwater collection itself, local and constant wind situations are also explained in this chapter. These include land and sea breeze, mountain and valley winds and the trade winds. Clouds touching the ground, for example in mountainous regions (as seen in figure 14), give also a good environment for collecting water by atrapanieblas. These can be stratiform clouds formed under trade inversions or clouds formed during monsoon seasons. Also cloud forests present a good environment with persistent fog. But first, the reasons for higher air humidity in warm climates are explained. A higher air humidity leads to higher amounts of water present in the fog and therefore to a higher water yield by atrapanieblas. The global and local climate systems of the tropics are discussed by *Nieuwolt* (1977) and *Hastenrath* (1991).



Fig. 14: Stratiform clouds in Chile (Pilar Cereceda)

2.5.1 Higher Humidity in Warm Climates

The higher humidity of air in warm climates, and therefore higher amounts of water vapor in the air, leads, upon cooling of the air, to the precipitation and condensation of higher amounts of water in comparison to colder water saturated air. This leads to

higher liquid water contents in warmer environments in fogs of similar composition, shown in figure 15.

One factor for the higher humidity is the presence of warm air masses which can take up and retain more water in the form of water vapor than cold air. Humidity is also enhanced by a higher evapotranspiration, which is the flow of water vapor out of the ground, from water surfaces, and from plants and animals into the atmosphere. Evapotranspiration is enhanced in conditions where air has a higher capacity to take up water vapor, a higher

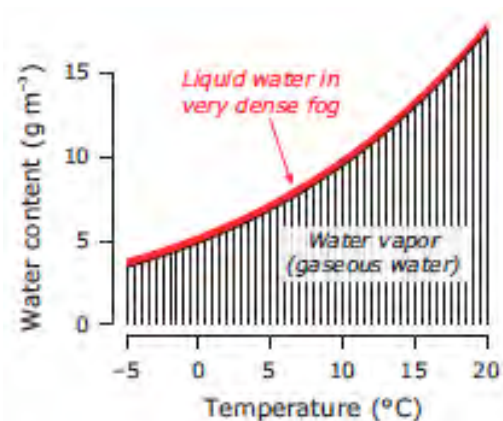


Fig. 15: Liquid water content in relation to temperature (Eugster 2008)

energy input through solar radiation occurs, and where there is a higher turbulence of the air in the lower parts of the atmosphere. All these conditions are present in warm climates, the latter due to stronger convections, explained in the following subchapter. Over water surfaces the evaporation is stronger since water is freely available with no limits to its availability. This leads to higher liquid water content in advection fogs forming over oceans or large lakes in low latitudes. The highest humidity of the atmosphere can be found in lower altitudes below 2000 m. Therefore the formation of orographic fog is more likely and lasting in warm climates, where warm air from lower altitudes flows up a mountain slope due to valley winds (see chapter 2.5.2.2.2). If the mountains are close to the coast, sea breeze (see chapter 2.5.2.2.1) may also have an influence on the upward motion of the air.

2.5.2 Global and Local Wind Systems

Stable winds in warm climates play an important role in the conditions needed for fog collection. For the mesh of the collector to be able to collect water during a fog event it is necessary for the wind to push the fog with its droplets through the mesh. Apart from pushing the fog through the collectors, winds also transport fog or clouds or are essential for fog or clouds to form.

Global wind currents, such as trade winds and monsoons, lead to persistent airflows and recurring climatic conditions, which are producing fog or low-level clouds. Advection fog or stratiform clouds forming over water areas can be pushed onshore by the sea breeze. Orographic fog is generated by warm, moist air flowing up a mountain slope transported by valley winds. These weather systems are explained in the following subchapters.

2.5.2.1 Global Wind Systems

Global wind systems are responsible for the trade winds and the monsoons. These winds are persistent, respectively occur periodic, giving good conditions for fogs or low level clouds to form.

2.5.2.1.1 Trade Winds

The trade winds can provide a regular fog source. Trade winds are part of the Hadley Cells. In general, these are stable global air circulations over the northern and the southern hemisphere with air flowing away from the equator at a height of 8000 to 12000 m and towards the equator low to the ground. The airflows low to the ground and towards the equator are called trade winds. These air circulations are relatively

stable over the Pacific and Atlantic Ocean with constant trade winds blowing from ENE in the northern and from ESE in the southern hemisphere over the open oceans. Trade winds are very persistent and can form regular orographic fog and clouds when blowing over mountainous islands.

2.5.2.1.2 Monsoons

Clouds generated during monsoons can also be harvested when touching the ground in mountainous areas. Monsoons are wind currents over the large landmasses of Africa and Asia seasonally changing their direction significantly. This change is mainly caused by the strong seasonal change of ground temperatures on these continents. Different from water, ground heats up and cools down rapidly. The Asian winter monsoon winds are mainly flowing off the Asian continent from December to March and the Asian summer monsoon winds are mainly flowing from the Indian Ocean to Asia (see figure 16). Particularly the summer monsoon transports very humid warm air, which precipitates as rain over southern Asia. On its way, the clouds can be intercepted by mountain ranges, as is the case at the coast in southern Oman. In Africa, only the summer monsoon brings humid warm air to the southern coast of West Africa where it causes rainfall.

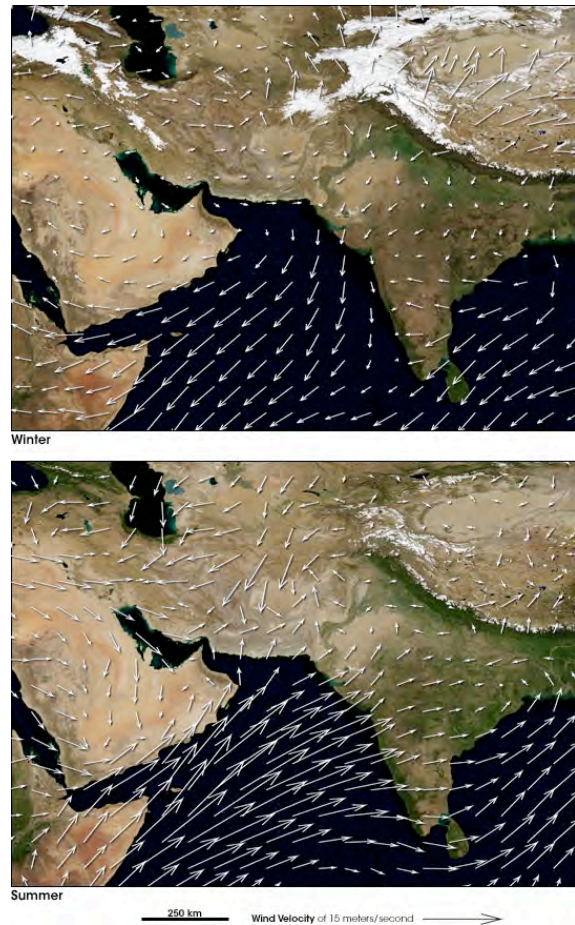


Fig. 16: Asian monsoon: Monsoon winds during winter and summer over the Arabian Sea (www.monsoonsafaris.com)

2.5.2.2 Local Winds in Warm Climates

Local wind systems generate regular winds between land and water areas and in mountainous regions, due to convection in warm climates.

2.5.2.2.1 Sea Breeze and Land Breeze

Coastal wind systems have a clear diurnal cycle in warm climates (see figure 17). During the day the land heats up fast whereas the water surface stays cool. The water stays cooler because the water dissipates the heat through turbulence, waves, and direct penetration and absorption over thick layers of water. This results in the development of a local convectional system, the sea breeze. Wind is blowing from the water to the land close to the earth's surface. During the night this effect is reversed. As the land cools off fast, the temperature of the water surface changes only slowly. A wind off the land is the consequence, the land breeze. Usually, the sea breeze is stronger than the land breeze.

2.5.2.2.2 Valley Wind and Mountain Wind

In mountainous regions a steady flow of wind up the slopes during the day and downwards during the night can be observed (see figure 18). This effect is caused

when air at same altitudes heats up at different rates. During the day the surface of the mountain and its surrounding air heats up whereas the air at the same altitude over the valley stays cooler. As air at higher altitudes is normally cooler than at lower altitudes, this effect is greater at higher elevations of mountain slopes. The result is a steady flow of air up the mountain slope called valley or anabatic wind. Again, this effect is reversed during the night. Due to radiation loss the mountain surface cools off more rapidly and a flow of air downwards is the result. This wind is called mountain or katabatic wind.

Both land and sea breeze, and valley and mountain winds have a higher intensity and are more constant at lower latitudes. Here the solar radiation is higher throughout the year resulting in higher surface temperatures. Also the climates have a lesser variability throughout the year.

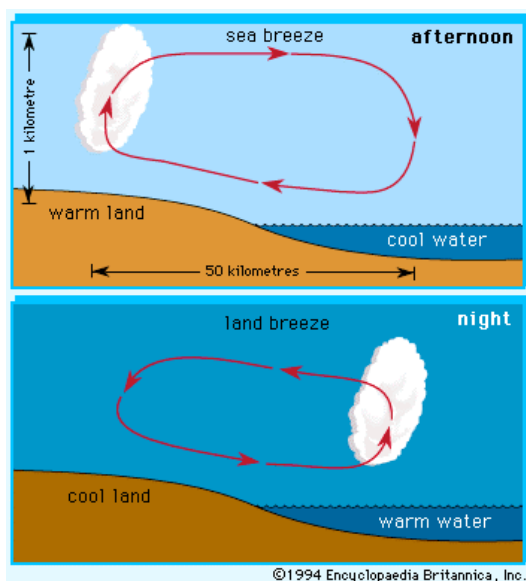


Fig. 17: Coastal convection
(www.britannica.com)

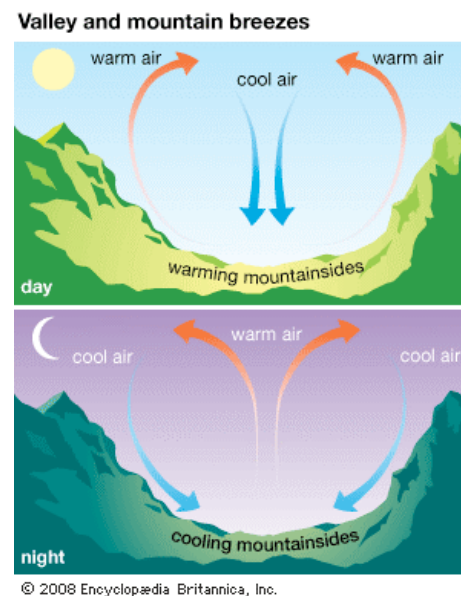


Fig. 18: Mountain convection
(www.britannica.com)

2.5.3 Fog Formation Enforced by Cold Ocean Currents

Over cold ocean currents advection fog can accumulate, given enough humidity in the atmosphere. If this happens near the coast, the sea breeze pushes the fog towards the land. Along the coasts of West Africa and the Pacific coasts of North and South America run major cold ocean currents. These are the Peru Current, also known as Humboldt Current, in the Pacific Ocean off Peru and Chile and the California Current off California. In the Atlantic Ocean off the coast of Africa these are the Canary Current off northern Africa and the Benguela Current off southern Africa. The courses of ocean currents are shown in figure 19. The cold currents are parts of large gyres in the North and South Pacific and the North and South Atlantic and all flow towards the equator. Over these currents a high frequency of fog days can be observed. The currents are also important in respect of trade inversions explained further down.

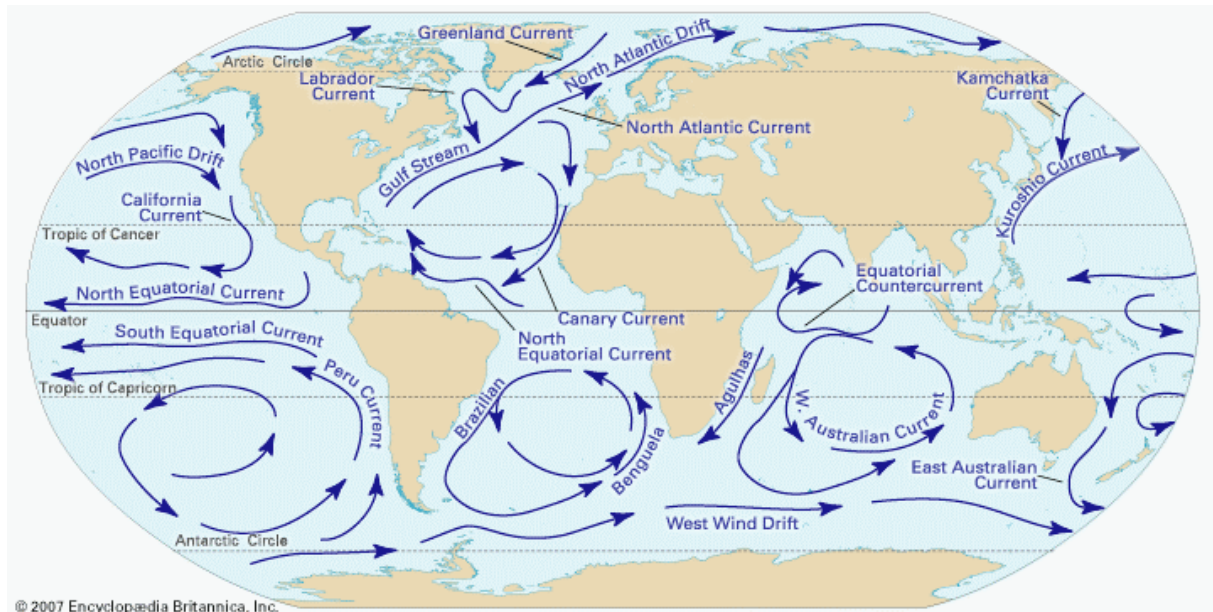


Fig. 19: Ocean currents (Merriam-Webster)

2.5.4 Trade Inversion

The advection fog over cold ocean currents is intensified by the trade inversions occurring in these areas. An inversion layer occurs when the air temperature increases with increasing altitude instead of cooling down. An inversion layer prevents a vertical upward movement of air and thus traps warm air, which normally rises, underneath it. The trade inversions are persistent inversions over the major cold ocean currents in the Pacific and the Atlantic Ocean. The occurrence of the trade inversions is, among other factors, also induced by the currents. In the Atlantic the trade inversions stretch westward as far as the Caribbean in the North Atlantic, and to South America in the South Atlantic. In the Pacific they reach Hawaii in the North and Tahiti in the South Pacific. The thickness of the inversions is about 325 m to 400 m. The lowest inversion bases are to be found near the coasts of Africa over Cape Verde and at the latitudes of Alexander Bay in South Africa, and also near the coasts of North and South America at the latitudes of southern California in the USA, and Peru and Chile. The heights of the inversion bases are between 400 and 500 m at these locations. The frequency is also the highest in the areas where the inversion base is the lowest. The inversion off the coast of California is persistent throughout the year. In northern Chile the frequency of inversions is up to 98% of the year. In the Atlantic the inversions are most frequent in the boreal winter and especially towards its end in March. In the boreal summer they are rare, which is the rainy season in Africa in these areas. Off the coast of East Africa, a trade inversion with an inversion base at about 1000 m can be found in the Indian Ocean near Durban, South Africa, in the boreal summer. The effects of trade inversions on the local weather systems are very humid air and no rainfall. The trade inversions impede warm moist air from rising but keep it close to the surface. The warm moist air is transported towards the equator by the trades. These are persistent wind currents low to the ground flowing towards the equator, as explained above. They are part of the Hadley Cells, a stable global air circulation. The trade inversions hinder the clouds from growing thick enough to produce rainfall. The lack of rainfall leads to arid climates at the regions with the lowest trade inversions. This is shown in the world map of the climate zones in figure 20. Arid climates are to be found in western North and South Africa and western North and South America, where the inversion bases are the lowest.

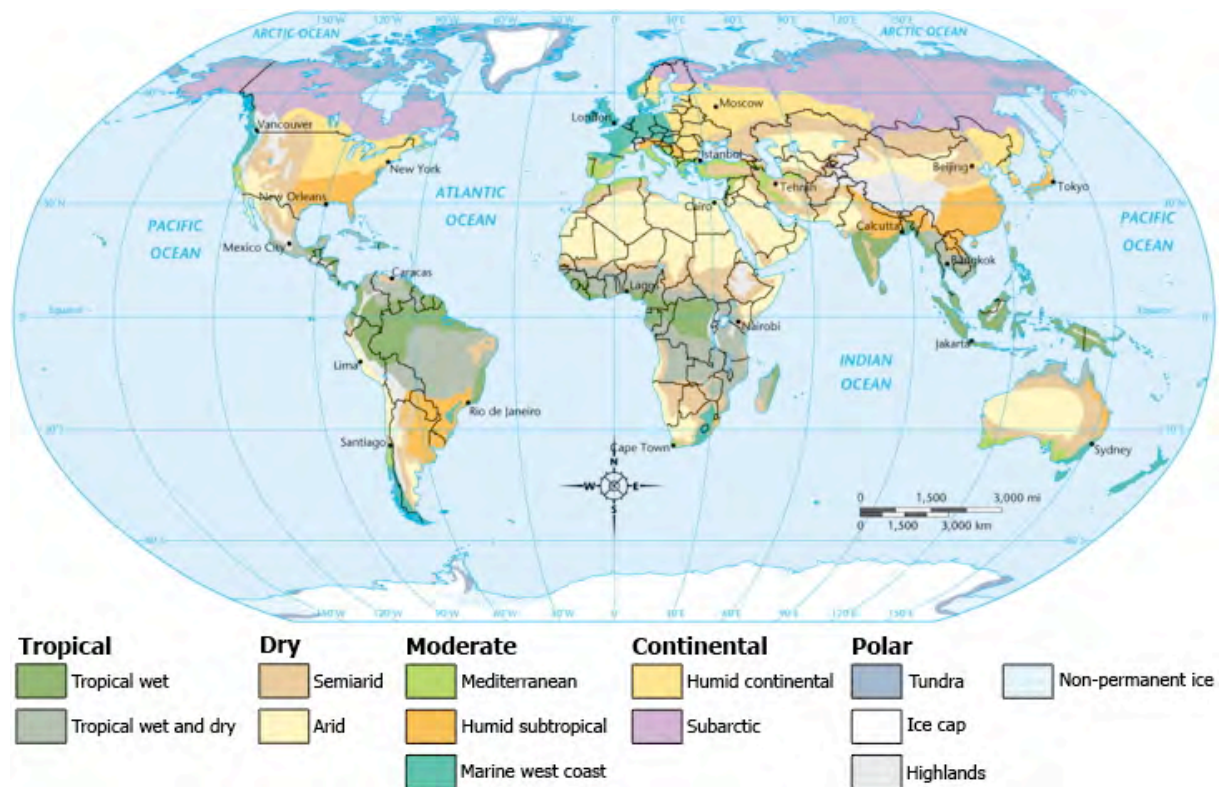


Fig. 20: World Climate Zones (www.greeneducationnetwork.com)

But there are persistent stratiform clouds at low altitudes underneath the inversion layer. The cloud tops can be tapped by the inversion base or extend into the inversion layer (Sedlar and Tjernström 2009). These clouds are therefore at low altitudes and can touch mountains close to the coast when blown landwards by sea breezes. If the stratiform clouds are still present over land in the evening, the ground cools off less rapidly and the clouds may still persist into the night. Also, due to the high evaporation, the lack of vertical transportation of the moisture, and the cold-water currents flowing up to the surface, there is a high rate of fog days in these regions. As these are generally very dry regions with almost no rainfall, gaining water out of the local fog or clouds is a very important water resource.

2.6 Topography

The topography is also an important factor in the use of *atrapanieblas*. The water yield is higher when *atrapanieblas* are built on mountain ridges or windward slopes close to the sea. The reason for this is that moist air from the sea will be pushed up the slope producing orographic fog. Also, advection fog can form over the sea close to the coast and low-level clouds can touch the mountain ridges. Large inland lakes provide good conditions for fog harvesting, as well, especially if they are surrounded by mountains. Advection fog forming over large inland lakes and the sea can be pushed onshore by the sea breeze. The airflow from the sea or lake, which is high in humidity, should not be obstructed prior to the collection site, as this will result in an early precipitation of the water in the atmosphere. However in warm climates the moist air can be transported over large distances over lowlands, as is the case at the fog collection sites in Nepal (Apigian 2005).

2.7 Ideal Regions for Fog Harvesting Worldwide

Because of the higher air humidity, the constant local winds, the cold ocean currents, the trade inversions, and the trade winds, ideal climates for setting up fog collectors can be found mainly in low latitudes. In respect of the trade inversions, it can be distinguished between

- advection fog being formed under the trade inversions and blown towards land by the sea breeze. This condition is present at the coasts of California, Mexico, Peru, Chile, the Cape Verde Islands, and the countries of north and southeast Africa, Morocco, Western Sahara, Mauritania, Senegal, Namibia, and South Africa.
- stratiform clouds pushed towards the coast by the sea breeze and being intercepted by mountains or mountain ranges located close to the coast. This is, among other locations, the case in northern Chile and the Table Mountain in South Africa.

At mountain ranges near the coast the frequent formation of orographic fog can be expected. But mountain ranges at a greater distance to coastlines can be reached by warm humid air as well, and produce high amounts of orographic fog. In low latitudes winds can transport humid air some hundreds of kilometers inland over lowlands while in high latitudes the air is transported merely 10 – 20 km (*Hastenrath* 1991). This effect can be observed, among other locations, at the southeastern foothills of the Himalayas, where periodically, during the summer monsoon, warm moist air from the Bay of Bengal and the Ganges plains flows up the slopes resulting in orographic fog (*Apigian* 2005). Large inland lakes can also be a factor for stable frequent fog events. If these are surrounded by mountains, the fog event turns out even stronger due to the stable up-flowing winds pushing the advection fog to the slopes and generating orographic fog there at the same time. The Victoria Lake in Africa is a good example for such conditions. Mountainous tropical islands, such as Hawaii, are also a reliable fog source due to the persistent trade winds. The world map in figure 21 shows an overview of sites, where the use of *atrapanieblas* has been investigated and is possible.



Fig. 21: World Map of Sites suitable for Fog Collection (in reference to Cereceda)

Montane cloud forests are also reliable locations for collecting water out of fog, or rather in this case the clouds. These forests are located in tropic mountainous regions where the clouds touch the ground and therefore envelope the forest. This can be at an altitude of 800 – 1500 m but also at condensation levels of high mountains, which are at altitudes of 2300 – 3800 m. Cloud forests can be found in tropical regions all around the world (see figure 1 and figures A1-A3 in the appendix A). Also in moderate climates a regular enclosure of mountains by clouds is possible (*Tiedemann 2001*).

In the regions aforementioned the amount of water collected in months with high frequencies of fog events can be over 30 l/m²/day (*Apigian 2005*).

3 Fogwater Quality in Alto Patache, Chile

In some regions the water collected by *atrapanieblas* does not have drinking water quality in respect to the guidelines set by the World Health Organization (WHO). Depending on the environmental conditions at the site of the *atrapanieblas*, the water can be very acid and can contain heavy metals, as observed in Alto Patache by *Sträter* (2009).

Water vapor in the atmosphere already has a natural pH of about 5.6, caused by its equilibrium with the CO₂ of the atmosphere. But the pH of fog and cloud droplets can be significantly below 5.6. This can be caused by the chemical constituents of aerosols, originating in anthropogenic emissions and natural sources such as dust, or the emission of dimethylsulfide (DMS) from the oceans, which become incorporated in the droplets. Chemical processes taking place inside the droplets are also a cause.

The analyses of fogwater collected in Alto Patache, Chile, by *Sträter* (2009) showed that the water has an average pH of 3.3 and high concentrations of some trace metals. To be consumed safely and without hazards to the health the water from the fog collectors has to be treated prior to the distribution to the local population.

In this chapter, the site Alto Patache with its climate conditions, which are favorable for fog water collection, is introduced. Furthermore, possible factors influencing the water quality of the collected water in Alto Patache are explained. Comparing the constituents of the water of Alto Patache with the WHO guidelines, possible negative effects on the health of the consumer and materials used in water distribution caused by this water are also described in this chapter.

3.1 The Site Alto Patache

Alto Patache lies approximately 60 km south of Iquique in northern Chile and has a high rate of fog events. It is a research area of the *Centro del Desierto de Atacama* (CDA) situated on the ridge of a mountain range, the Cordillera de la Costa (see figure 22), about 800 m above sea level and merely 2 km inland of the coast. It lies at the edge of the Atacama Desert, one of the driest deserts in the world. Along the coast flows the cold Peru Current. This current and the trade inversion, which is very low in this region, play a major role in the formation of fog, which then flows over the ridge. Advection fog and low-level stratiform clouds, touching the ground on the mountain ridge, are pushed towards the coast and over the mountain range by a steady sea breeze during the day. Also orographic fog is quite frequent, even though not as frequent as advection fog and stratiform clouds. Usually the fog events start in the afternoon and last well into the night.

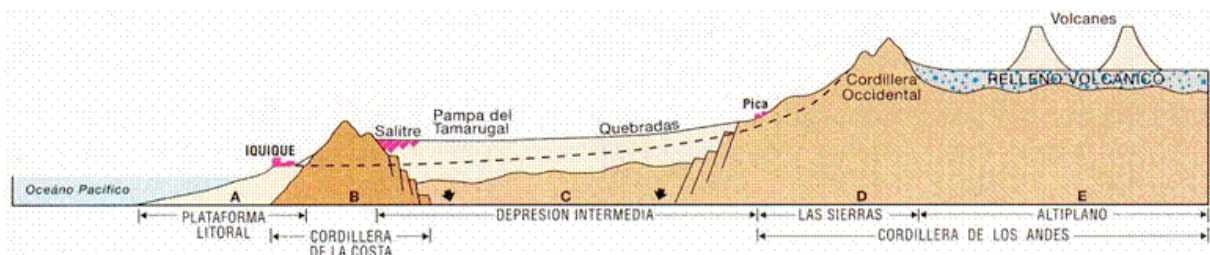


Fig. 22: Cross-section of northern Chile (Velásquez et al. 2004)

Figures 23 and 24 depict yield measurements conducted by the CDA in Alto Patache. Figure 23 shows the total amount of water in liter collected with an SFC in one month for the months of the years 2003 and 2004. Figure 24 shows the average yield per m² and day for every month of the years 2003 and 2004. The graphs show

that the most intensive fog events are in the months July through November. The maximum yield is achieved in August, September, and October and can be up to 20 l/m²/day. The average water yields were 7.3 l/m²/day in 2003 and 5.9 l/m²/day in 2004.

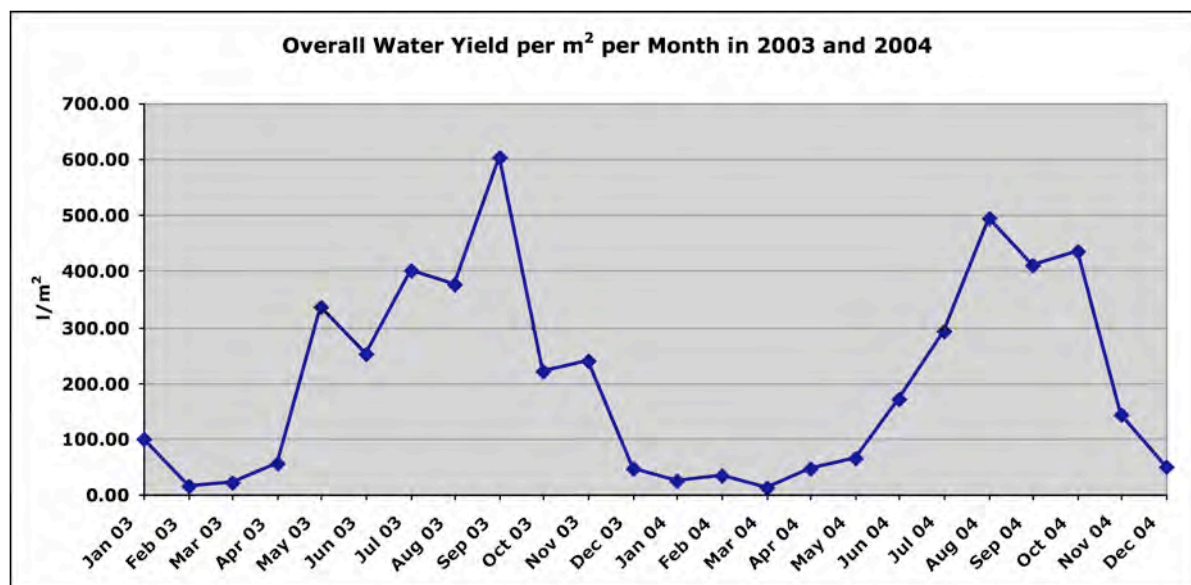


Fig. 23: Total water collected in Alto Patache per month (according to CDA)

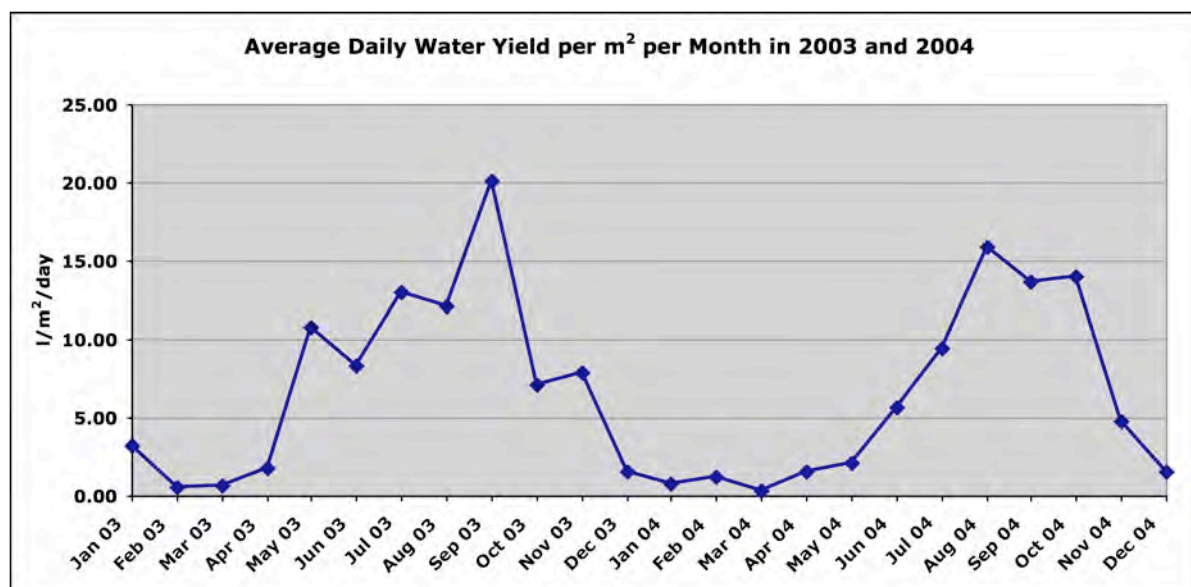


Fig. 24: Average daily water yield in Alto Patache per month (according to CDA)

3.2 Origin of Water Quality in Alto Patache

Different factors play a role in the low pH and the high concentrations of some trace metals in the water collected by the atrapanieblas in Alto Patache. Among possible factors are the properties of water droplets in fog and clouds, anthropogenic influences, the emission of dimethylsulfide (DMS) by the Pacific Ocean, and the accumulation of dust in the fog collectors. A combination of these factors causing the water quality of Alto Patache is very likely.

3.2.1 Properties of Droplets in Fog and Clouds

Fog droplets can have high concentrations of ions and trace metals due to their physical properties. Oxidation processes take place inside the droplets, as well, leading to a further acidification.

In comparison to rain droplets, the concentrations in fog droplets are 10 – 50 times higher. The reason for this, explained by *Stumm and Morgan* (1996), is the small diameter of the fog droplets, which is much smaller than the diameter of rain droplets (see figure 25). The chemical constituents are much more concentrated in the smaller droplets of fog than in the rain droplets which have the same condensation nuclei with the same chemical constituents but are more diluted.

The origins of these chemical constituents are aerosols, either condensation nuclei or scavenged by droplets, or gases in the atmosphere, being absorbed by fog droplets. As explained above, aerosols are essential in the formation of fog and clouds. The occurrence of aerosols in clouds is depicted in figure 28. Aerosols are distinguished between primary atmospheric aerosols and secondary aerosols. The primary atmospheric aerosols are made up of dust and smoke particles, and the secondary aerosols of constituents of the gas phase. Trace metals are more common in the coarse particles of the primary atmospheric aerosols which mainly originate from soils. These aerosols produce larger fog droplets, thus trace metals are rather to be found in large droplets. However, *Rao and Collett* (1998) also observed that in industrial regions trace metals are to be found in the gas phase, which constitutes the secondary aerosols. The secondary aerosols produce smaller fog droplets, thus leading, due to anthropogenic emissions, to higher trace metal concentrations in small droplets as well. Chemical and physical processes which take place when primary gaseous emissions interact are responsible for the formation of secondary aerosols (www.chemistry-dictionary.com). Fog droplets also act as collectors which take up local pollutants (*Stumm and Morgan* 1996).

The composition of the aqueous phase of fog droplets is affected by the dissolution of water-soluble components of the aerosols. Nitric acid, sulfur dioxide, and ammonia are among the soluble gaseous species (*Hoag et al.* 1999). According to *Singh et al.* (2001), these are the primary pollutants, which lead to acidic deposition. In the research carried out by *Hoag et al.* (1999), the overall scavenging efficiency for sulfate, nitrate, and ammonia was close to 60%. Sulfate (SO_4^{2-}) is removed by deposition of the fog droplets, but is also produced in the aqueous-phase of the droplets through the oxidation of sulfur dioxide (SO_2). In this oxidation process sulfuric acid (H_2SO_4) is formed, which is the conjugate base of SO_4^{2-} (*Stumm and Morgan* 1996). At the research site of *Hoag et al.* (1999) in the San Joaquin Valley, California, the production of sulfate was higher than the deposition. The most sulfate was produced in droplets with diameters of about 20 μm . *Pandis and Seinfeld* (1990) also discovered that sulfate is highly enriched in the droplets with the highest liquid

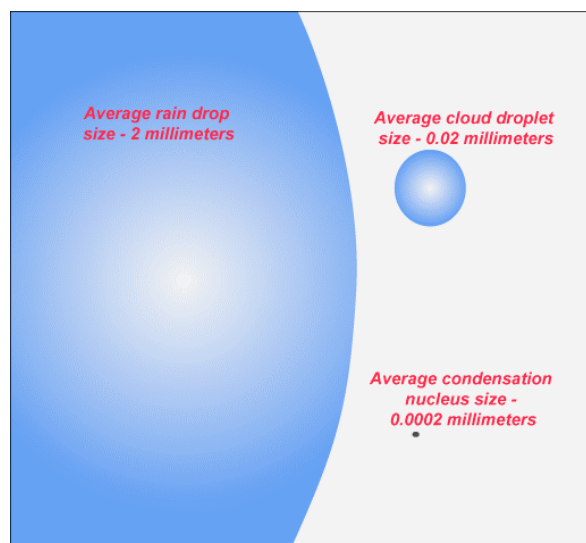


Fig. 25: Size differences between cloud and rain droplets (apollo.lsc.vsc.edu)

water distribution in fog. The fog droplets having most of the liquid water also scavenge the nitric acid in the atmosphere, which is produced in the gas-phase.

Iron and manganese can catalyze the sulfur autooxidation in the fog droplets, but only in an alkaline environment (*Rao and Collett 1998*).

Hoag et al. (1999) and *Collett et al. (2001)* observed in California that the smaller droplets are more acidic and contain higher concentrations of nitrate, sulfate and ammonium than larger droplets. However, research about the solute concentrations in small and large droplets with theoretical models and with field experiments show contradictory results. *Pandis and Seinfeld (1990)* calculated fog droplet concentrations through theoretical models and came to the conclusion that, due to the faster growth of small droplets ($> 10 \mu\text{m}$) compared to large droplets, the dilution is higher in small droplets and therefore large droplets have higher solute concentrations (see figure 26). On the other hand, field measurements in the Po Valley, Italy, conducted by *Ogren et al. (1992)*, showed that the solute concentration declines continuously with increasing droplet size (see figure 27). Agreeing with the theoretical model also used by *Pandis and Seinfeld (1990)*, *Ogren et al. (1992)* were unable to give a definite explanation for their observations. The inhibition of the activation of the droplets, due to subsaturation or altered surface tension, which hinders the uptake of water, might be reasons for the continuous decline of solute concentrations. Inaccuracy in the measurements could also be a reason. Yet, the observation that fog with a low water yield, and therefore smaller droplets, had higher concentrations was also made by *Sträter (2009)* in Alto Patache.

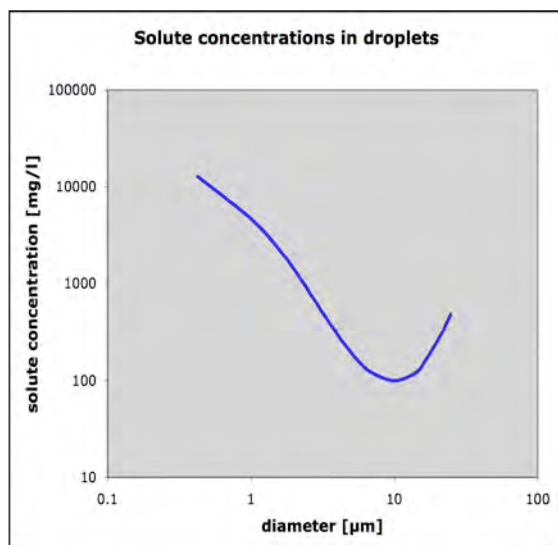


Fig. 26: solute concentrations in droplets (in reference to *Pandis and Seinfeld 1990*)

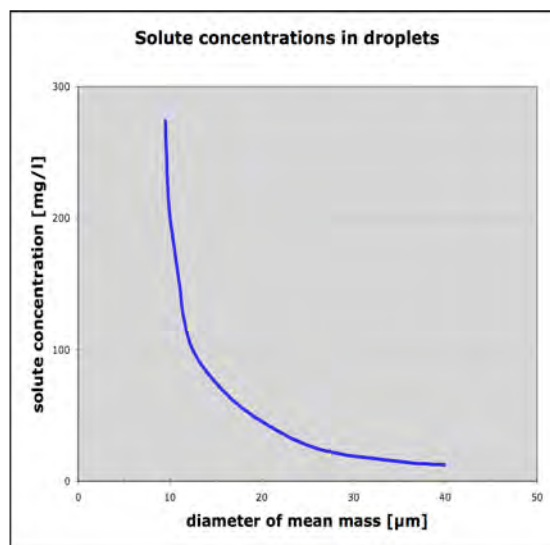


Fig. 27: solute concentrations in droplets (in reference to *Ogren et al. 1992*)

Daum et al. (1984) who studied the acidity and constituents in stratiform clouds observed that the concentrations increased as the liquid water content of the clouds decreased. Cloud droplets have very similar properties as fog droplets, as the process of formation of cloud droplets on aerosols (see figure 28) is the same as of fog droplets. In the cloud droplets the main ionic species were H^+ , NH_4^+ , SO_4^{2-} , and NO_3^- , as well. Comparing the constituents of the cloud droplets and of the interstitial air in the stratiform clouds, it was shown that H^+ was highly enriched in the aqueous phase. Also the larger part of NO_3^- and SO_4^{2-} was to be found in the cloud droplets. It was concluded that much of the H^+ , and therefore the acidity, came from absorbed interstitial gases being converted in the droplets. This agrees with the results of

research on fogwater. According to *Daum et al.* (1984), NO_x and SO_2 in the gas phase are the sources for enhanced acidity in cloud droplets compared to aerosols. At times with higher concentrations of gaseous NO_x or SO_2 , the cloud droplets had higher concentrations of nitrate or sulfate. The liquid water content was higher and the pH lower at lower altitudes of a stratiform cloud. Substantial volumes of air are processed in clouds, and clouds can transfer aerosols and gas over large distances (*Stumm and Morgan 1996*).

At the site El Tofo (see chapter 2.4.1) at the coast north of La Serena in Chile, *Schemenauer and Cereceda* (1992) analyzed the fogwater and the deposition in the nets of the atrapanieblas. (The analysis of the deposition is explained in more detail below.) From their research they found that the major ions present in the collected water from a fog event are the same as the ones being found in the deposition of aerosols. This suggests that the clouds scavenge the aerosols as they pass through them. This conclusion is further supported by the fact that the ion concentrations in the fogwater diminish during a fog event until they reach the background concentration of constituents being marine-derived. The concentrations in the air diminish as the fog and cloud droplets form on the aerosols and thus remove them from the air (*Stumm and Morgan 1996*). This leads to lower concentrations in later fog and clouds.

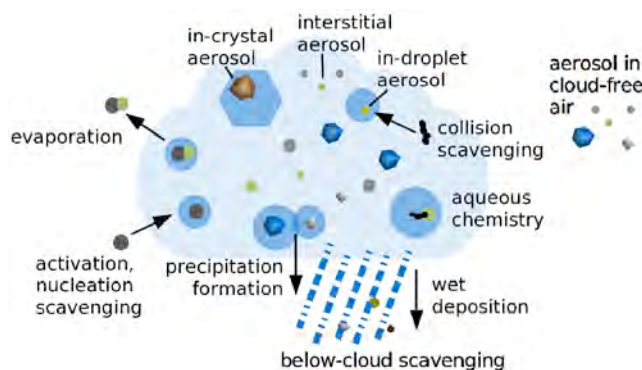


Fig. 28: Aerosols in clouds (*Hoose et al. 2008*)

The aerosol mass in the atmosphere can also increase when fog dissipates. After the dissipation of the fog the products of the dissolved species, which had undergone reactions in the droplets, remain in the aerosol phase. The mass of these products can be higher than its mass before the fog event (*Hoag et al. 1999*).

Fog and cloud droplets are therefore presenting an environment in which the accumulation of chemicals, originally present in the atmosphere in aerosols or in the gas phase, and chemical reactions, especially oxidation, are enhanced. This leads to high concentrations of acid and the accumulation of trace metals, which was also observed in Alto Patache.

3.2.2 Anthropogenic Influence

An extreme example of the dispersion of aerosols with anthropogenic origin is shown in the satellite photography in figure 29 (*visibleearth.nasa.gov*). It shows the dispersion of aerosols in the air over the lowlands of the Ganges and the Brahmaputra, and the Bay of Bengal. As mentioned above, warm, moist air flowing periodically over these lowlands from the Bay of Bengal is forming fog at the foothills of the Himalayas which can be harvested by atrapanieblas. On this passage it is very likely that the air scavenges the aerosols, which leads to acidic fogwater. High concentrations of trace metals in the collected water are also very probable.

Even though Alto Patache is a remote site, far away from large industrial areas except for one coal-fired power plant, the anthropogenic influence may play a significant role in the low pH and high trace metal concentrations of the collected water. According to *Cereceda* and *Larraín*, the power plant lies approximately 4.5 km to the west, but at the leeward side of the *atrapanieblas* during most of the time, and therefore the direct influence on the fog water composition can be presumed to be low. *Sträter* (2009) examined the flow of the air masses arriving at Alto Patache through a backward trajectory analysis. The backward trajectory analysis showed that the air masses are traveling north along the coast of Chile for 48 to 72 hours, or over 1800 km. On their way they pass the main industrial areas of Chile and therefore it is quite possible that they gather sulfur dioxide (SO_2) and heavy metals from the emissions of the industries. SO_2 is by far the most produced sulfur emission in the industry and in the energy production through fossil fuel combustion (*Seinfeld and Pandis* 2006). The fog and cloud droplets absorb SO_2 . In the water droplets SO_2 is transformed into sulfuric acid (H_2SO_4) and sulfate (SO_4^{2-}) through oxidation, as explained above. Due to the presence of high concentrations of heavy metals in the water samples with high enrichment factors, *Sträter* (2009) concluded that the main concentration of sulfate in the fog water is rather an anthropogenic source than an accumulation induced by oceanic emission of dimethylsulfide (DMS) and its atmospheric oxidation.

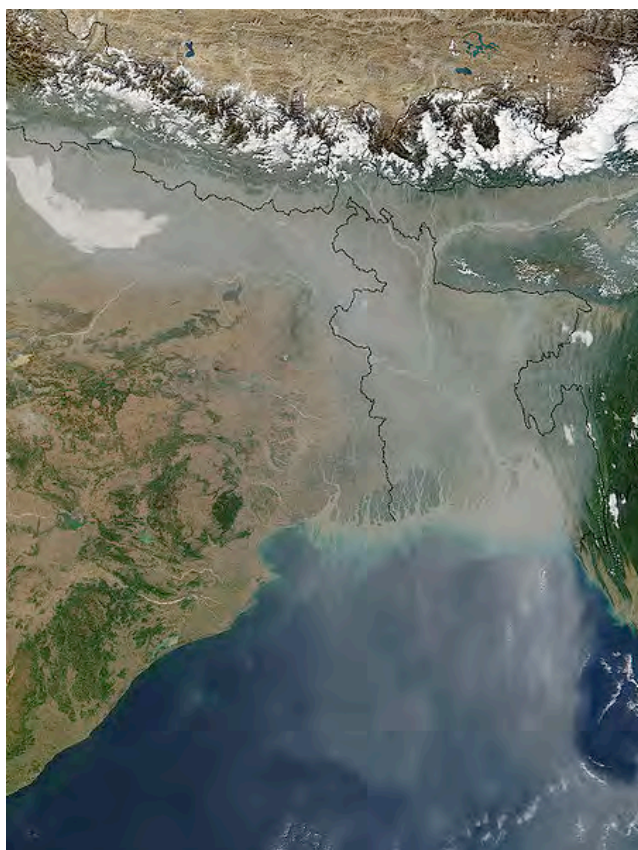


Fig. 29: Aerosols over Northern India and Bangladesh (*Jacques Descloîtres*)

the emissions of the industries. SO_2 is by far the most produced sulfur emission in the industry and in the energy production through fossil fuel combustion (*Seinfeld and Pandis* 2006). The fog and cloud droplets absorb SO_2 . In the water droplets SO_2 is transformed into sulfuric acid (H_2SO_4) and sulfate (SO_4^{2-}) through oxidation, as explained above. Due to the presence of high concentrations of heavy metals in the water samples with high enrichment factors, *Sträter* (2009) concluded that the main concentration of sulfate in the fog water is rather an anthropogenic source than an accumulation induced by oceanic emission of dimethylsulfide (DMS) and its atmospheric oxidation.

3.2.3 Dimethylsulfide

Nevertheless, dimethylsulfide (DMS) emissions from the Pacific can contribute to the high sulfate concentrations of the fogwater. By comparing the ion concentrations of the fogwater at El Tofo with the ion concentrations of seawater through the enrichment factors in the manner of *Ahmed et al.* (1990), *Schemenauer and Cereceda* (1992) found out that only the SO_4^{2-} concentrations were high throughout the whole fog event in comparison to seawater. A possible source of the excess SO_4^{2-} could be the emission of DMS and other sulfur species from the ocean as the cold waters off the coast of Chile are organically rich. *Benbow* (1995) investigated the production of DMS and its effects on climate. DMS is produced in large amounts in productive marine environments and is volatile. On the majority, non-sea-salt sulfates (NSS-SO_4^{2-}) are formed by DMS. As aerosols, these sulfates compose the majority of cloud condensation nuclei over ocean areas. Therefore an elevation of SO_4^{2-} concentrations in fog and cloud droplets through DMS emissions along the Chilean coast is quite possible.

DMS and other naturally occurring aerosols, on which fog and cloud droplets can form, and their origin are depicted in figure 30.

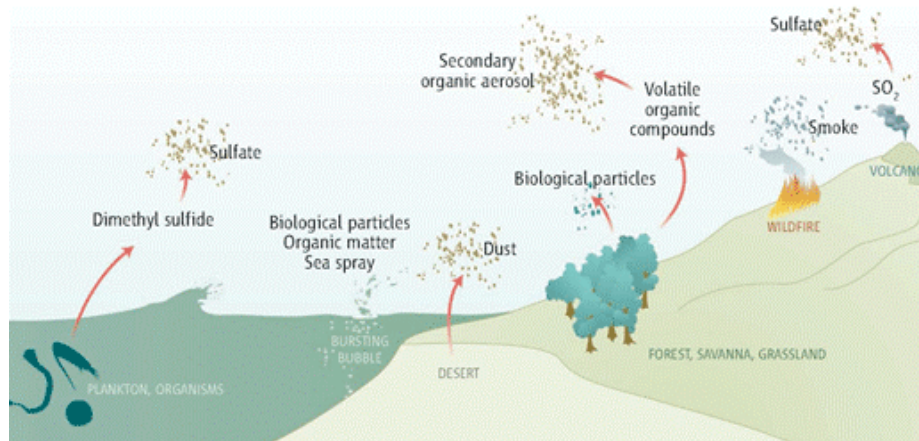


Fig. 30: Natural occurring aerosols (Andreae 2007)

3.2.4 Deposition in Atrapanieblas

The deposition of dust and aerosols in the nets and the drip rail (see figure 31) of the atrapanieblas most likely influence the water quality, as well. Besides other sources, the main origin of this deposition is local soil.

Schemenauer and Cereceda (1992) collected dust and aerosols with an atrapaniebla especially built for their investigation. Consisting of vertical Teflon fibers, it was a modification of the design by the ASRC mentioned above. By rinsing this atrapaniebla with distilled water in between fog events, *Schemenauer and Cereceda* (1992) collected the dust and aerosols accumulating for 25 hours in the fibers, whose composition could be determined by comparing the composition of the distilled water before and after the rinse. The ion and the trace metal concentrations in the rinse water containing dust and aerosols were considerably higher



Fig. 31: Deposition in drip rail

than in the distilled water. These dust and aerosols also accumulated in the large atrapanieblas used for the water collection in El Tofo. This is also the case in the atrapanieblas set up in Alto Patache. *Schemenauer and Cereceda* (1992) compared the deposition in the Teflon atrapaniebla with the local soil through enrichment factors calculated in the manner of *Ahmed et al.* (1990) and *Galloway et al.* (1982). Through this they found out that the soluble constituents of the soil are found again to a large percentage in the soluble constituents of the dust and aerosols in the atrapaniebla. The water-soluble elements, whose origin could be traced back to local soil, were aluminum, iron, and titanium. The water-soluble elements arsenic, copper, strontium, and vanadium may originate in local soil. If fogwater comes into contact with soil dust containing these trace metals, moderate to high concentrations of these trace metals will be available to the water. With the results of the water analysis made by *Sträter* in 2009, *Sträter* (2009) also make this observation. The water

samples show high concentrations at the beginning of a fog event, which decrease during the fog event. One explanation for this can be that the dust is being washed off during the fog event. The water in the storage tank has up to three times higher ion concentrations than the water samples collected directly at the net. This can be caused by the mixture of the collected water with the washed off deposition of the nets.

The chemical processes in fog and cloud droplets, the scavenging of aerosols and the washing off of deposition in the nets of atrapanieblas can all lead to low pH and high concentrations of chemicals in water collected by atrapanieblas. The pH and concentrations of chemicals depend on the location of an atrapaniebla. Therefore prior to the construction of atrapanieblas in a new location an analysis of the fogwater should be done and an adequate water treatment for the collected water should be taken into consideration. Chapter 4 gives suggestions for treating the collected water of Alto Patache.

3.3 *WHO Standards*

Starting in 1983, the *WHO* has published three editions of the Guidelines for Drinking-water Quality, which is revised frequently and takes the newest scientific researches on chemicals found in drinking water in consideration. The latest addendum of the third edition was published by the *WHO* in 2008. The limiting values given in this paper are based on the guideline values of the *WHO*.

The drinking water quality proposed in the Guidelines by guideline values is safe drinking water. This means that the consumption of drinking water, which has the water quality defined by the Guidelines, does not affect the health if consumed over a lifetime. Apart from consumption it is also suitable for all usual domestic purposes. This includes personal hygiene. The guideline values are most important for water consumed by infants, young children, debilitated adults and elderly, since they are at greatest risks of waterborne diseases.

However, the application of the Guidelines is not suitable for water which is required for pharmaceutical or industrial use and therefore has to be of higher quality.

Due to local conditions the national standards set by governments can differ from the guidelines proposed by the *WHO* (2008). These conditions can be of local or national environmental, economic, social and cultural nature.

Nevertheless, the limiting values for drinking water used in this work are based on the guideline values set by the *WHO* (2008) and not on the standards set by the Chilean government. The Chilean standards apply to the region of Alto Patache, where the water samples were taken from fog collectors. But the natural conditions in which atrapanieblas can be operated are also to be found in other countries and the quality of the obtained water along the Pacific coast of South America north of Chile is possibly of similar nature as the water collected in Alto Patache. The standards of these countries may differ from one another. In order to have the same basis for the treatment of the water obtained through atrapanieblas along the Pacific coast, the *WHO* guideline values are taken as the standard in this paper.

As stated above, the lifelong consumption of drinking water with chemical concentrations below the *WHO* guideline values won't affect the health of the consumer. There are only guideline values given by the *WHO* for drinking water chemicals, when higher concentrations of a chemical constituents have negative effects on health. Other restrictions to the concentrations are given by the odor and

taste thresholds of some chemicals. These can be lower than the health-based guideline values and alter the water in its odor or taste before it becomes harmful to health. The odor threshold and the taste threshold are only estimations for the average person since the ability of detecting odors or tasting substances differs among humans (ATSDR 2001).

Table 3: WHO guideline values (WHO 2008)

Chemical	WHO guideline value	Odor threshold	Taste threshold	Alteration of appearance
pH	6.5 – 9.5 (recommendation)	n.s.	n.s.	n.s.
Ions				
Ammonia	n.s.	1.5 mg/l	35 mg/l	n.s.
Calcium	n.s.	n.s.	100 – 300 mg/l	n.s.
Chloride	n.s.	n.s.	250 mg/l	n.s.
Chlorine	5 mg/l	n.s.	0.3 mg/l	n.s.
Fluoride	1.5 mg/l	n.s.	n.s.	n.s.
Magnesium	n.s.	n.s.	< 100 mg/l	n.s.
Nitrate	50 mg/l	n.s.	n.s.	n.s.
Nitrite	0.2 mg/l	n.s.	n.s.	n.s.
Phosphate	n.s.	n.s.	n.s.	n.s.
Potassium	n.s.	n.s.	n.s.	n.s.
Sodium	n.s.	n.s.	200 mg/l	n.s.
Sulfate	n.s.	n.s.	250 – 1000 mg/l	n.s.
Trace metals				
Aluminum	n.s.	n.s.	n.s.	0.1–0.2 mg/l
Arsenic	10 µg/l	n.s.	n.s.	n.s.
Cadmium	3 µg/l	n.s.	n.s.	n.s.
Chromium	50 µg/l	n.s.	n.s.	n.s.
Copper	2000 µg/l	n.s.	n.s.	n.s.
Iron	n.s.	n.s.	0.3 mg/l	< 0.3 mg/l
Lead	10 µg/l	n.s.	n.s.	n.s.
Manganese	0.4 mg/l	n.s.	0.1 mg/l	0.05 – 0.1 mg/l
Nickel	70 µg/l	n.s.	n.s.	n.s.
Selenium	10 µg/l	n.s.	n.s.	n.s.
Zinc	n.s.	n.s.	4 mg/l	3 mg/l

Table 3 gives an overview of the WHO guideline values for pH, the major ion concentrations and the major trace metal concentrations to be found in drinking water. The odor and taste thresholds are given as well, if existing and being lower than the guideline value. Some constituents may alter the appearance of drinking

water by color or texture if present in higher concentrations. If this is the case, these concentrations are also given in table 3.

Even though a higher or lower pH normally found in natural waters does not pose an immediate threat to health, the recommended range of pH for drinking water lies between 6.5 and 9.5. A detailed explanation for this recommendation is given further down in chapter 3.5.1, in which the effects for the constituents of the collected water in Alto Patache, which have higher concentrations than the *WHO* guidelines, are explained.

Ammonia, calcium, chloride, magnesium, phosphate, potassium, sodium and sulfate do not have a guideline value given by the *WHO*. However, ammonia can be detected by odor at a concentration of 1.5 mg/l and by taste at 35 mg/l. The taste threshold is at 100 – 300 mg/l for calcium, at 250 mg/l for chloride, lower than 100 mg/l for magnesium, at 200 mg/l for sodium, and at 250 – 1000 mg/l for sulfate.

The concentrations of fluoride can affect the health above a concentration of 1.5 mg/l. This is also the case for nitrate at a concentration above 50 mg/l and for nitrite, which can form out of nitrate in anaerobic conditions, at 0.2 mg/l.

Chlorine is widely used in disinfection of drinking water and therefore the guideline value and the taste threshold are mentioned here. These are 5 mg/l and 0.3 mg/l respectively.

Phosphate and potassium have neither guideline values nor odor and taste thresholds.

Among the trace metals, aluminum, iron, and zinc do not have *WHO* guideline values. But a concentration higher than 0.1 – 0.2 mg/l of aluminum can lead to deposition of aluminum hydroxide flocs. Iron may be detectable by taste at concentrations above 0.3 mg/l and turbidity and color can develop even below this concentration. Zinc can be tasted above 4 mg/l and below 3 mg/l the water can appear opalescent and upon boiling a greasy film can be developed.

The guideline value for arsenic is 10 µg/l, for cadmium 3 µg/l, for chromium 50 µg/l, and for copper 2000 µg/l. Guideline values are also given for lead, manganese, nickel and selenium, which are 10 µg/l, 0.4 mg/l, 70 µg/l, and 10 µg/l respectively. Manganese may already be noticed at concentrations above 0.1 mg/l by taste and at 0.05 – 0.1 mg/l, manganese in water may lead to deposits in the distribution system.

3.4 Water Quality in Alto Patache

The fogwater in Alto Patache was analyzed by *Sträter* (2009) in July and August in 2008. During the time of their research on site, they had nine fog events, eight with advection fog and one with orographic fog. The fogwater analyzed was pure fogwater. The water in a water tank, which collected the fogwater from an *atrapaniebla*, was also analyzed. They observed a low pH, high ion concentrations of ammonia and nitrate, and high trace metal concentrations of arsenic, iron, lead, and selenium. The pH was the lowest and the concentrations the highest in the orographic fog. The water in the fogwater storage tank was a mixture of fogwater of advection and orographic fog and also included the washed off deposition in the net of the *atrapaniebla*. Therefore this water also had higher mean concentrations than the fogwater of the advection fog. Table 4 shows the pH and the ion concentrations and table 5 the trace metal concentrations of the fog events and the fogwater storage tank.

The pH was the lowest in the orographic fog with 2.5. The advection fog had a mean pH of 3.3 and the water tank 3.1. Of the ion concentrations only nitrate exceeded the *WHO* guideline values of 50 mg/l with 136.4 mg/l in the orographic fog and 62 mg/l in the water tank. The mean ammonia concentration was in the fog events and the water tank above the odor threshold of 1.5 mg/l. With 50 µg/l in the orographic fog and with 28 µg/l in the water tank, arsenic was significantly over the *WHO* guideline value of 10 µg/l. In the advection fog a maximum concentration of 16 µg/l was measured. With 48 µg/l in orographic fog and 30 µg/l in the water tank, lead exceeded the *WHO* guideline value of 10 µg/l. Also here the maximum concentration measured in advection fog exceeded the *WHO* guideline value with 20 µg/l. Selenium only exceeded the *WHO* guideline value of 10 µg/l slightly with 12 µg/l in the orographic fog and the water tank. Iron exceeded the taste threshold of 300 µg/l in the orographic fog (870 µg/l) and the water tank (310 µg/l). Also a coloration of the water due to the high iron concentration is possible.

Table 4: PH and ion concentrations in Alto Patache (in reference to Sträter 2009)

Chemical	Mean in advection fog [mg/l]	Min. in advection fog [mg/l]	Max. in advection fog [mg/l]	Orographic fog [mg/l]	Mean in fogwater storage tank [mg/l]	WHO guideline values
pH	3.3	2.9	3.5	2.5	3.1	6.5 – 9.5 (recomm.)
Ions						
Ca ²⁺	2.40	0.64	6.01	8.42	13.81	<i>n.s.</i>
Cl ⁻	23.8	6.0	42.6	109.9	67.4	<i>n.s.</i>
F ⁻	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1.5 mg/l
K ⁺	0.98	0.21	1.68	8.60	3.48	<i>n.s.</i>
Mg ²⁺	2.19	0.60	3.53	11.55	7.42	<i>n.s.</i>
Na ⁺	16.3	3.9	27.6	85.1	59.8	<i>n.s.</i>
NH ₄ ⁺	1.59	0.45	3.78	6.67	2.88	<i>n.s.</i>
NO ₃ ⁻	17.4	5.0	34.7	136.4	62.0	50 mg/l
PO ₄ ³⁻	0.20	< 0.10	0.48	6.34	1.62	<i>n.s.</i>
SO ₄ ²⁻	42.3	12.5	96.1	350.6	144.1	<i>n.s.</i>

Table 5: Trace metal concentrations in Alto Patache (in reference to Sträter 2009)

Chemical	Mean in advection fog [µg/l]	Min. in advection fog [µg/l]	Max. in advection fog [µg/l]	Orographic fog [µg/l]	Mean in fogwater storage tank [µg/l]	WHO guideline values [µg/l]
As	9.1	< 5.0	16	50	28	10
Cd	< 0.5	< 0.5	0.9	2.0	1.2	3
Cr	< 2.5	< 2.5	< 2.5	< 2.5	< 2.5	50
Cu	49	< 5.0	130	420	220	2000
Fe	< 200	< 200	210	870	310	<i>n.s.</i>
Mn	< 200	< 200	< 200	< 200	< 200	0.4
Ni	< 5.0	< 5.0	5.3	17	8.5	70
Pb	< 10	< 10	20	48	30	10
Se	< 5.0	< 5.0	8.0	12	12	10
Zn	< 50	< 50	60	90	110	<i>n.s.</i>

Calcium and magnesium have low concentrations, which leads to soft water. The maximum hardness was achieved in the orographic fog event with 8.42 mg/l calcium and 11.55 mg/l magnesium. The hardness was

$$c(\text{Ca}^{2+} + \text{Mg}^{2+}) = \frac{8.42 \text{ mg/l}}{40.08 \text{ mg/mmol}} + \frac{11.55 \text{ mg/l}}{24.31 \text{ mg/mmol}} = 0.69 \text{ mmol/l}.$$

The range of soft water is 0 – 1.25 mmol/l (*Mutschmann and Stimmelmayer* 2007).

3.5 Effects of the Water on Health and Materials

The low pH and the high concentrations of some ions and trace metals, in reference to the WHO guideline values, in the water collected in Alto Patache can have negative effects on health and the endurance of materials used in the water distribution. This chapter describes these negative effects, which are explained in detail by the *WHO* (2008).

3.5.1 pH

A low pH in water alone has no immediate health effects on humans. For example, the pH of orange juice can be as low as 2.6 (*Fine* 1978). Therefore the *WHO* does not give a health-based guideline value.

But the level of pH has chemical and biological effects on the water itself. Different aquatic microorganisms prefer environments with different levels of pH and the solubility and the chemical reactions of substances are influenced by the pH.

The pH is significant in the corrosion reactions and a solution with lower pH is corroding materials made out of metals. In distribution systems made out of metal pipes this can cause leakage of the piping (see figure 32) and the formation of deposition (see figure 33). If this happens, a good chemical and microbial quality of the water is not assured anymore. Other parts, such as tanks, valves and pumps, may also corrode, leading to significant damage in the distribution system.



Fig. 32: Corrosion of metal pipe
(www.fractureinvestigations.com)



Fig. 33: Deposition in metal pipe due to corrosion
(www.h2osurplus.com)

Another consequence of corrosion is the dissolution of the metal of which the pipes are made of. This can lead to higher concentrations of lead, copper and other metals used in piping in the drinking water, which may have negative long-term effects on the health of the consumers.

On the other hand, in the process of disinfection with chlorine, a lower pH is favorable. Water treated with chlorine will need a longer contact time in alkaline water or the free residual chlorine level needs to be higher at the end of the contact time to assure adequate disinfection. A lower pH will also reduce the formation of THMs, which are disinfection by-products and considered to be toxic. However, a lower pH leads to increased formation of halogenated acetonitriles, which also have a negative effect on health.

For these reasons, the optimum pH for drinking water is in the range of 6.5 – 9.5.

3.5.2 Ion Concentrations

Of the elevated concentrations of ions, only nitrate can have a negative effect on health. Nitrate can cause methaemoglobinaemia, especially among infants (also known as blue-baby syndrome). In anaerobic conditions nitrate can be transformed by bacteria to nitrite, which is harmful above a concentration of 0.2 mg/l if taken in long-term.

Ammonia is not harmful to health, but the odor threshold of ammonia is 1.5 mg/l and the taste threshold 35 mg/l. Apart from the taste and odor problems, which can occur due to high ammonia concentrations, the disinfection efficiency can be compromised by ammonia. Also nitrite can form in the distribution system, and filters installed for manganese removal may break down.

3.5.3 Trace Metal Concentrations

Of the elevated concentrations of trace metals, lead, arsenic, and selenium can affect the health of the consumer.

Lead is especially toxic on the central and peripheral nervous systems. High concentrations of lead are most harmful to children and pregnant women.

High concentrations of arsenic in drinking water can cause dermal lesions and peripheral neuropathy, a damage to the peripheral nervous system (www.ninds.nih.gov). Arsenic is also considered carcinogenic inducing skin, bladder and lung cancer.

Selenium causes so called selenosis, if consumed long-term in high dosis. The symptoms of selenosis are nail brittleness, hair loss and neurological abnormalities (ATSDR 2003).

The elevated concentrations of iron may alter the taste and can lead to turbidity and coloration of the water.

4 Water Treatment of Fogwater in Alto Patache

The analyses by *Sträter* (2009) of the water collected in Alto Patache clearly show that the water has to be treated prior to consumption as drinking water. In this treatment the pH has to be raised and the concentrations of some trace metals have to be reduced. For this reason laboratory experiments were conducted with collected fog water to lower the pH and precipitate arsenic with calcium carbonate (CaCO_3).

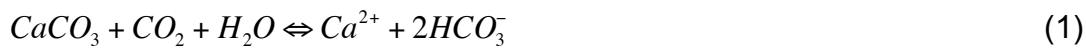
This chapter introduces the methods for raising pH and reducing arsenic concentrations, and discusses the results of the experiments with CaCO_3 . The last subchapter is about first flush systems, which separates the collected water with high concentrations, and the application of CaCO_3 in sand filters.

4.1 Treatment Methods

4.1.1 Raising pH

One of the most important treatments of the water in Alto Patache is the raising of the pH, since the low pH of 3.3 causes corrosion in the distribution system, which then leads to contamination and loss of water, and dissolution of metal material causing higher concentrations of heavy metal in the drinking water. Raising of pH can be achieved by bringing the water in contact with alkaline media. This can be either the filtration of the water over calcium carbonate (CaCO_3) or dolomite ($\text{CaMg}(\text{CO}_3)_2$), or the addition of alkalis. Alkalis most suitable for water treatment are calcium hydroxide ($\text{Ca}(\text{OH})_2$), sodium hydroxide (NaOH), and sodium carbonate (Na_2CO_3) (*Mutschmann and Stimmelmayer* 2007).

Calcium carbonate (CaCO_3) is a mineral which is found in great quantity in nature (*Langmuir* 1997). When water comes in contact with CaCO_3 the following equation describes the chemical process:



The concentrations of carbon dioxide (CO_2), hydrogen carbonate (HCO_3^-), and carbonate (CO_3^{2-}) are correlated. The equations of this correlation are the following:



The direction of the equations is dependent on the fractions of the constituents on the total concentration and thus their saturation. The fractions are dependent on the pH, as shown in figure 34. Below a pH of 4.3 the concentration of HCO_3^- can be neglected. This leads to a higher occurrence of this initial reaction equation from left to right at low pH:



This equation shows a direct removal of H^+ and therefore a faster increase in pH. As the pH rises, the water can take up more HCO_3^- and the reaction slows down. Depending on the pH and the concentrations of CO_2 and HCO_3^- , equation 2 changes the direction of the reaction from right to left. As the fraction of CO_2 diminishes with rising pH the reaction slows down even more. Above a pH of 8.3 the concentration of CO_2 is very low and can be neglected (*Johannsen* 2004). A pH higher than 8.3 cannot be expected when treating acidic water with CaCO_3 (*Green et al.* 2006).

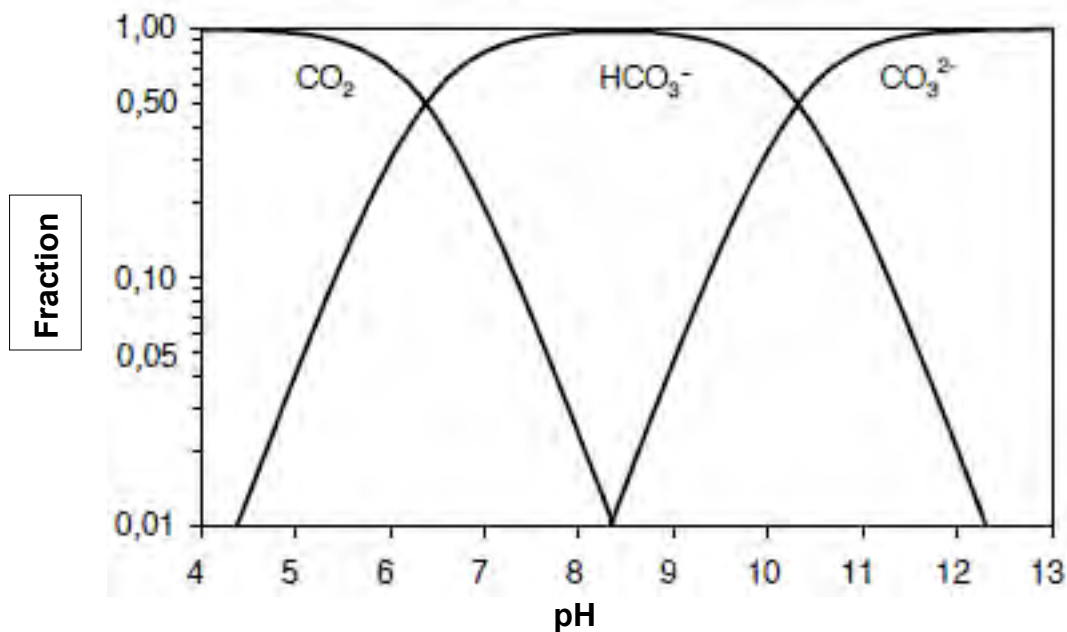
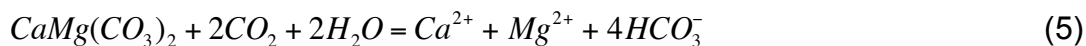


Fig. 34: Fractions of forms of carbonic acid at 10°C (Johannsen 2004)

After calcium carbonate (CaCO_3), the occurrence of dolomite ($\text{CaMg}(\text{CO}_3)_2$) is the second largest of the carbonate minerals. The dissolution of dolomite is described by this equation:



The process of raising the pH of water in dissolution with dolomite is similar as with calcium carbonate. The dissolution is influenced by the same factors as CaCO_3 and in general the dissolution is slower than calcium carbonate, but the saturation of dolomite in water is higher than of calcium carbonate (Langmuir 1997).

Calcium hydroxide ($\text{Ca}(\text{OH})_2$) is very effective in raising the pH. But it is very difficult to dose because it is very soluble and has a very fast reaction with water. It is very easy to overdose and reach a pH of 10 and above (Green et al. 2006). Sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3) are also difficult to handle and can be overdosed as well (Mutschmann and Stimmelmayer 2007).

The reaction of calcium carbonate is much slower. It is a safe material to handle and there is no risk of overdosing, as the pH of treated water with CaCO_3 won't exceed 8.3 (Green et al. 2006).

Through economic analysis it is shown that CaCO_3 is the least expensive alkaline media for acid neutralization (Hedin et al. 1994; cited by Sibrell et al. 2006).

For these reasons and its ability of reducing the concentrations of trace metals (explained in more detail in chapter 4.1.2) CaCO_3 is very suitable for the use in the treatment of the water of Alto Patache.

4.1.2 Reduction of Arsenic Concentration

There are different methods for the removal of arsenic from drinking water. Arsenic can be precipitated and then removed by coagulation. Using adsorbents, such as fly ash, iron oxide (Fe_2O_3), iron hydroxide ($\text{Fe}(\text{OH})_3$), or aluminum oxide (Al_2O_3), one can reduce arsenic concentrations in drinking water as well. Arsenic can also be removed by lime precipitation, ion exchange, or reverse osmosis.

Arsenic exists in water in two inorganic forms, arsenite (As^{3+}) and arsenate (As^{5+}). At a neutral pH, As^{3+} is existent as non-dissociated, uncharged species and is hardly removable by precipitation or adsorption. As^{3+} can be oxidized to As^{5+} in the water treatment by ozone, UV irradiation, activated carbon, potassium permanganate, or manganese oxides. *Driehaus and Jekel* (1993a) recommend in their study the use of potassium permanganate or manganese oxides. Due to the very high surface area of the water droplets in fog and clouds oxidation of As^{3+} to As^{5+} in the droplets can proceed. But the oxidation process mainly takes place at pH 6 – 9 (*Stöver* 1993). The arsenic in the water of Alto Patache was reduced to a high percentage by CaCO_3 . This suggests that the main arsenic was present as As^{5+} .

As^{5+} can be removed by precipitation and coagulation with ferric (Fe^{3+}) or aluminum (Al^{3+}) salts. *Jekel* (1993) explains with respect to this process that Fe^{3+} precipitates easily at pH 5 – 11, whereas Al^{3+} needs a pH of 6 – 7.2, otherwise there will be a high residual aluminum concentration in the treated water. The use of ferric salts is therefore preferable to the use of aluminum salts. At lower pH the efficiency of ferric salts is higher, therefore not a complete deacidification of the treated water prior to the precipitation and coagulation with ferric salts should be considered.

CaCO_3 is also effective in removing arsenic out of drinking water. According to *Jekel* (1993), the arsenic is removed through adsorption on the CaCO_3 particles or by forming insoluble Ca-arsenate. Dolomite may also be a possible agent for removing arsenic and raising the pH at the same time. But dolomite is less efficient than CaCO_3 (*Potgieter-Vermaak et al.* 2005).

Wang and Wu (2006) showed in their research, that, in particular at lower pH of about 4, arsenic can also be removed by Class C fly ash, which has a higher content of lime (5 – 30 wt. %). Lime consists of calcium oxide (CaO) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). But *Dutta et al.* (2009), who studied the leachability of fly ash under acidic conditions, showed that trace metals were largely released in acidic water, which could not be neutralized by the alkaline CaO present in the fly ash. Thus arsenic may again be leached out of the fly ash, once it has been retained, by the following acid water, if used for the fogwater in Alto Patache.

The adsorption of arsenic on iron hydroxide ($\text{Fe}(\text{OH})_3$) was investigated by *Driehaus and Jekel* (1993b). Iron oxide (Fe_2O_3) and iron hydroxide ($\text{Fe}(\text{OH})_3$) can be used in granular form as adsorbents. The research showed that the specific loading of the $\text{Fe}(\text{OH})_3$ with arsenic is higher at low pH. Aluminum oxide (Al_2O_3) can also be used as an adsorbent, but $\text{Fe}(\text{OH})_3$ has clear advantages. It has a far higher capacity and therefore has a longer operating life. It can be applied in a fixed-bed adsorption filter, which is easy to run, and only needs minor supervision.

Lime precipitation, ion exchange, and reverse osmosis are not considered to be feasible as a treatment of this water. Lime precipitation, in which $\text{Ca}(\text{OH})_2$ is added leading to a precipitation of CaCO_3 , which in turn adsorbs the arsenic, can only be done with hard water, which is not the case in Alto Patache. Ion exchange and reverse osmosis are too expensive to be operated in the water treatment of the water collected by the atrapanieblas (*Hörner* 1991).

By removing arsenic with the methods explained above an accumulation of arsenic takes place in the adsorption or filter media. The disposal of these media has to be paid special attention as these media contain high concentrations of arsenic.

4.2 Treatment of Water from Alto Patache with CaCO_3

During a personal visit to Alto Patache in the first week of December 2009 water harvested during one fog event by an *atrapaniebla* was collected in bottles. This water was treated with CaCO_3 and a filter system. In this experiment with fogwater from Alto Patache, the increase of the pH and the precipitation of arsenic was measured and analyzed.

4.2.1 Method

The fogwater was mixed with different masses of CaCO_3 under laboratory conditions. During the mixture the increase of the pH in relation to time was measured. Afterwards the water with increased pH was filtered through a filter consisting of layers of iron oxide in form of rusty nails, charcoal, and layers of washed sand in between. This filter was built after a design published by the *UNDP* (2005).

4.2.1.1 Water Collection in Alto Patache and Handling Prior to Experiment

6 l of fogwater was collected during this fog event in inert plastic bottles made out of polypropylene (*pers. comm. Saavedra*). The water ran from the drip rail through a plastic pipe of approximately 2.5 m of length before it was collected by the bottles. The bottles were cooled in a cooler with ice cubes for the three-day transportation to the laboratory of the University Santa María in Valparaíso. There the bottles were deep-frozen for further conservation. The water was not acidulated.

Some of the water was defrosted with a microwave oven at the first day of experiments. This resulted in higher concentrations and a lower pH in this water. This water was only treated with pure CaCO_3 (99%). The other experiments were carried out with water defrosted at room temperature. The water from the different bottles, and therefore from different periods of the fog event, was mixed before the experiments resulting in uniform concentrations and pH during the experiment.

4.2.1.2 Addition of CaCO_3

For the experiments, CaCO_3 with two different kinds of purities were used. One had a purity of 99%, the other one was technical CaCO_3 with a lower, unspecified purity (see figure 35).

The experiments, run with the technical CaCO_3 , consisted of different masses of CaCO_3 mixed with 500 ml of fogwater and following filtration with a filter consisting of iron oxide, coal, and sand (further explained in chapter 4.2.1.3). The masses of CaCO_3 were 25 g, 50 g, and 75 g, giving the three concentrations 50 g/l, 100 g/l, and 150 g/l. As each mass was weighed threefold, three sequences were run per mass. A sequence started with the addition of CaCO_3 to the water, which was stirred continuously with a magnetic stirrer, and the increase of pH over time was measured. This measurement was recorded manually with a stopwatch and an electronic pH meter in all experiments, therefore slight discrepancies can be assumed. The measurement was stopped after five minutes. Then the water was separated from the undissolved CaCO_3 with a vacuum filter (70 cm mercury column). The filter was a Sartolon Polyamid filter with a pore size of 0.2 μm . The water was still in contact with the CaCO_3 for about 10 minutes after the end of the pH-measurement. The next step, after the removal of the CaCO_3 , was the filtration of the water with the iron oxide, coal, and sand filter. The pH and the conductivity were measured before and after the sequence and in between every step.



Fig. 35:
Technical
 CaCO_3 (left)
and pure
 CaCO_3 (right)

The sequence with 100 g/l of CaCO_3 could only be evaluated twice, because the first sequence was done with the water of the microwave oven and therefore could not be compared with the following two sequences.

The CaCO_3 with 99% purity was mixed with water defrosted with a microwave oven, as explained above. 8 g of CaCO_3 was mixed with 250 ml of water, giving a concentration of 32 g/l. From the point where the CaCO_3 was added to the water, the increase of the pH over time was measured until a pH of 7 was reached. During this measurement the water was also stirred continuously with a magnetic stirrer, and the measurement was also done manually. The mixture was then allowed to stand for 48 hours to measure the maximum pH, which can be achieved by mixing water containing high trace metal concentrations and low pH with pure CaCO_3 . It was occasionally stirred during this time period. The conductivity was measured, as well, before and after each sequence. Three sequences were done of this experiment.

4.2.1.3 Sand Filter with Iron Oxide and Charcoal

The filter used in the last step consisted of rusty nails, charcoal, and sand, and was built after a design published by the *UNDP* (2005). The rusty nails provided a low cost source of iron oxide and the charcoal a low cost alternative to activated carbon. The purpose of the filter was the removal of arsenic from the water. The iron oxide adsorbs the arsenic. The following layer of charcoal reduces the higher iron concentration in the water after the contact with the iron oxide.

The filter was built in 1.5 l water bottles with a diameter of 7 cm, from which the bottoms were removed and which were suspended upside-down. The uppermost layer consisted of approx. 260 g nails of various sizes. The next layer was 3 cm of sand, followed by a layer of powdered charcoal. The diameter of the charcoal particles ranged from a few μm to 5 mm (see figure 36) and the charcoal had a total weight of approx. 125 g per filter. The lowermost layer consisted of 11 cm of sand. Three filters, shown in figures 37-39 were built, one for each mass. Unfortunately the flow rate of the filter for 50 g/l CaCO_3 was too low with almost no flow-through and

this filter could not be used. The cause is probably too fine charcoal used in this filter. The filter for 150 g/l was also used for the sequences with 50 g/l CaCO_3 .



Fig. 36: Charcoal particles used in filter

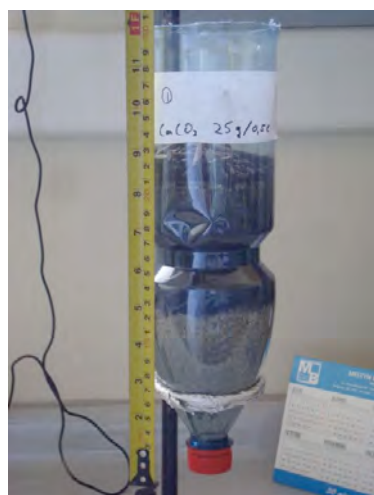


Fig. 37: Filter 1 (50 g/l CaCO_3)



Fig. 38: Filter 2 (100 g/l CaCO_3)



Fig. 39: Filter 3 (150 g/l CaCO_3)

4.2.2 Results and Discussion

The addition of CaCO_3 to the water with an initial pH between 3.23 and 3.29 caused a strong reaction with the pH increasing fast. But also the arsenic concentration was reduced significantly by the addition of CaCO_3 alone. The filter only had a minor influence on the residual arsenic.

The water samples from the experiment were analyzed about two months after the experiments were conducted. The samples were not acidulated and due to transportation the water samples were not cooled.

4.2.2.1 Increase of pH

The figures 40-42 show the increase of pH in the first five minutes after the different masses of technical CaCO_3 were added to the water defrosted at room temperature. The reaction between the water and the CaCO_3 resulting in an increase of the pH was very fast in the beginning. Mostly a pH of 6.5, which is the minimum recommended for drinking water, was already achieved after 12 to 16 seconds.

The initial pH was approx. 3.25 with the lowest pH of 3.23 in the water mixed with 25 g CaCO_3 and the highest pH of 3.29 in the water with 150 g/l CaCO_3 . The final pH was with approx. 8.05 also very similar in all sequences with different masses of CaCO_3 . The lowest pH of 8.02 was obtained with 150 g/l CaCO_3 and the highest pH of 8.10 with 100 g/l CaCO_3 . Also the water mixed with 50 g/l CaCO_3 reached higher pH than with 150 g/l CaCO_3 . This shows that the difference in the concentrations of CaCO_3 between 50 g/l and 150 g/l had no influence on the final pH. The slight differences in the final pH are very likely caused by slight differences in the chemical composition of the water. The water was mixed out of the four bottles of water filled during the fog event. Slight variations between mixtures are possible.

A difference between the additions of different masses of CaCO_3 can be seen in the velocity of the reaction. The reaction after the addition of 50 g/l CaCO_3 slows down gradually after about seven seconds at a pH of 5.5, whereas the reaction with 150 g/l CaCO_3 starts to slow down gradually after about 12 seconds at a pH of 6.5. Therefore a higher pH is reached slightly faster with 150 g/l CaCO_3 . After about 90 seconds all curves correspond once again and the pH rises only marginally.

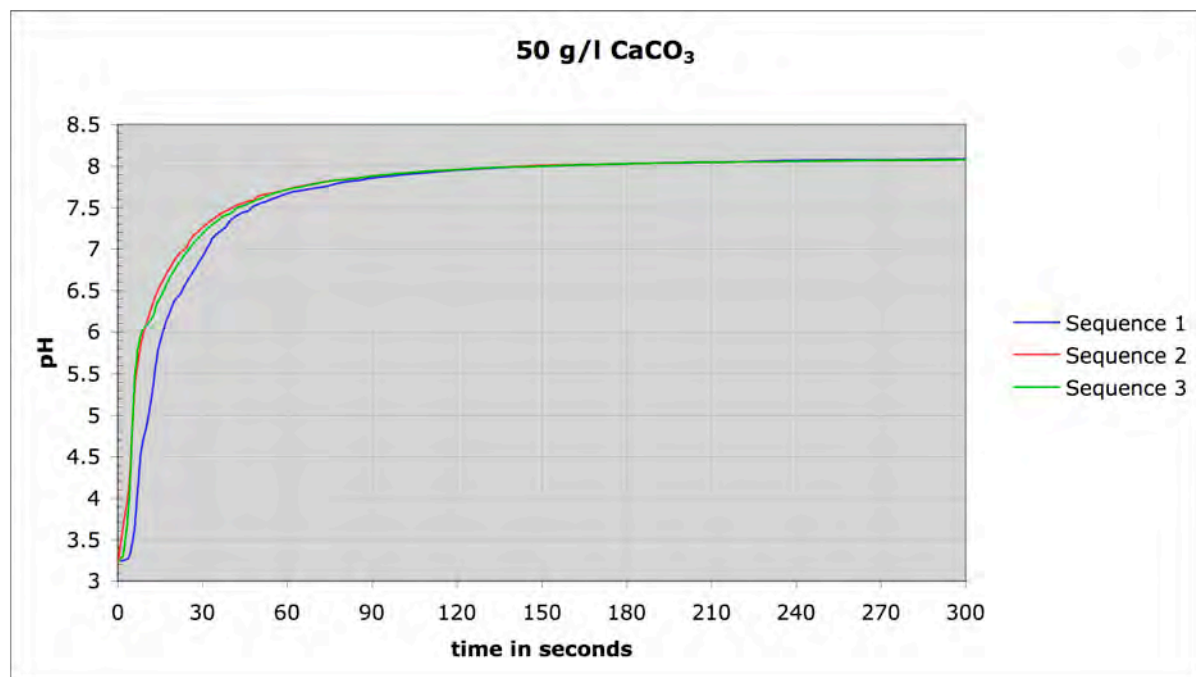


Fig. 40: Increase of pH over time with 50 g/l CaCO_3

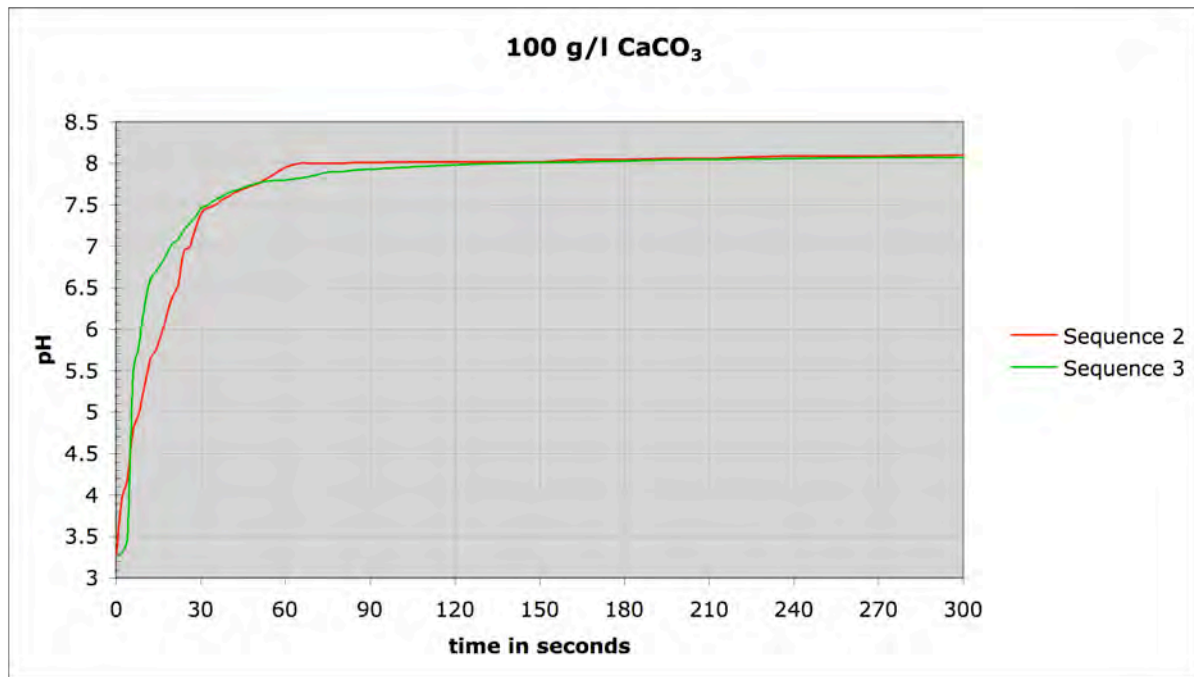


Fig. 41: Increase of pH over time with 100 g/l CaCO_3

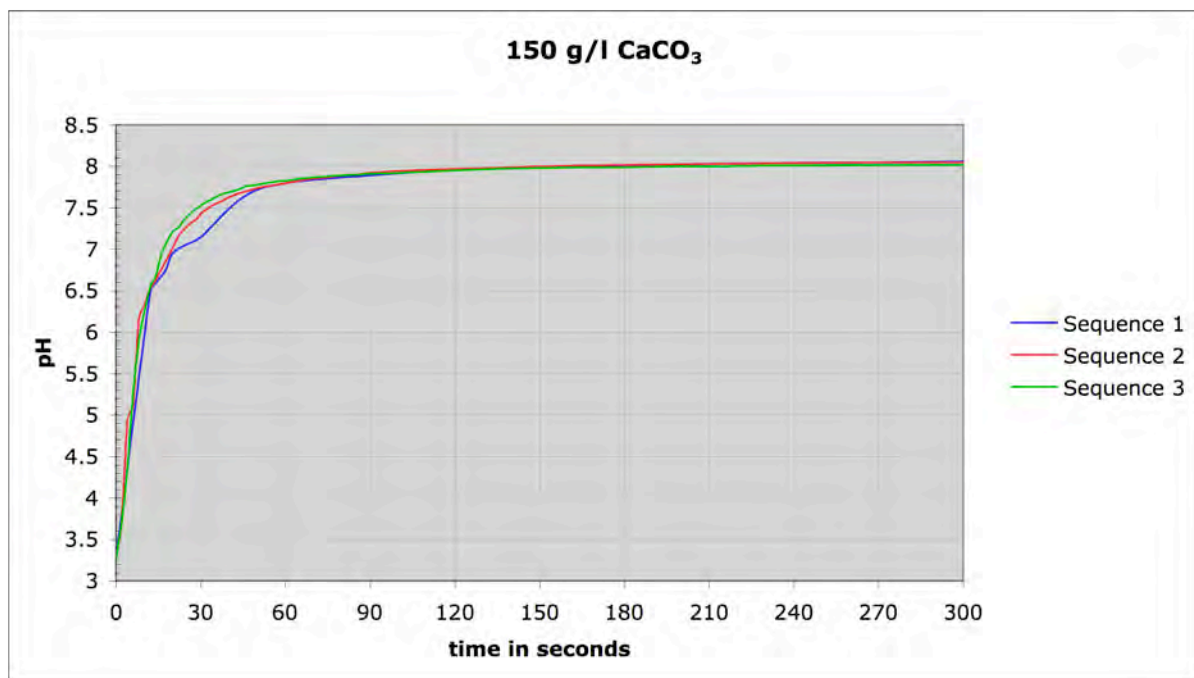


Fig. 42: Increase of pH over time with 150 g/l CaCO_3

The slowing down of the reaction between a pH of 5.5 and 6.5 can be explained by looking at the reaction equations 1-3 explained in chapter 4.1.1. As the pH rises, the water can take up more HCO_3^- and the reaction slows down. The fractions of CO_2 and HCO_3^- in respect to the pH can be seen in figure 34. Also the concentration of Ca^{2+} in the water increases, slowing down the activity in equation 1 from left to right. At a pH of about eight, the originally soft water is saturated with Ca^{2+} and the reaction stops.

The addition of 8 g CaCO_3 with a purity of 99% to 250 ml of water (32 g/l) with a low initial pH of 2.22 and 2.27 and higher chemical concentrations (see chapter 4.2.1.1) shows similar results (see figure 43). In the first ten seconds the increase of the pH is

very fast. After gradually slowing down, the increase is constant after three to four minutes. After 48 hours the water also reached a pH between 8.05 and 8.09.

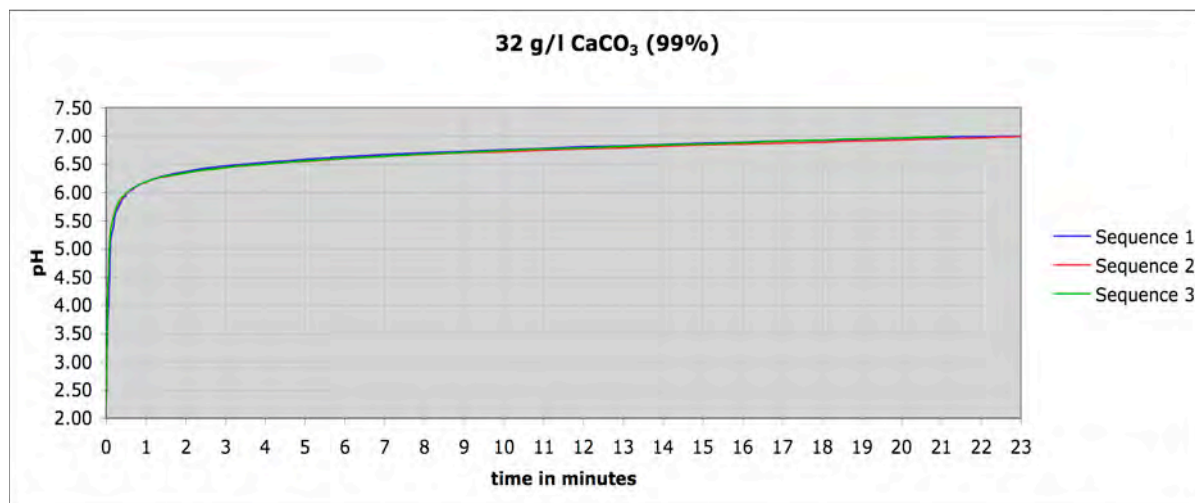


Fig. 43: Increase of pH over time with 32 g/l CaCO₃ (99%)

4.2.2.2 Reduction of Arsenic Concentration

The analysis of the treated water showed that already the addition of CaCO₃ to the fogwater, which had high concentrations of the trace metals iron, lead, arsenic, and selenium (see chapter 3.4) reduced the concentration of arsenic significantly (see table 6).

Table 6: Arsenic concentrations after addition of CaCO₃ and after filtration

CaCO ₃ concentration [g/l]	Original arsenic concentration [µg/l]	Arsenic concentration after CaCO ₃ [µg/l]	Arsenic concentration after filtration [µg/l]
50 g/l	24.1	2.3	1.9
50 g/l	24.1	2.2	1.7
50 g/l	24.1	2.6	1.2
100 g/l	24.1	3.7	5.2
100 g/l	24.1	2.7	2.6
150 g/l	24.1	4.4	6.4
150 g/l	24.1	4.1	3.7
150 g/l	24.1	4.1	2.9
32 g/l	140	8.4	-
32 g/l	140	8.6	-
32 g/l	140	6.2	-

The water treated with the technical CaCO₃ in different concentrations has an arsenic reduction of 80 – 90%. The original arsenic concentration of 24.1 µg/l matches approximately the arsenic concentration measured in the fogwater of the water tanks in Alto Patache (Sträter 2009). By adding CaCO₃ the arsenic concentration dropped below the WHO guideline value of 10 µg/l. It is interesting to notice that the arsenic concentration is higher after addition of higher amounts of CaCO₃. At this time an explanation for this cannot be given.

The CaCO₃ with a purity of 99% also reduced the arsenic concentration significantly from originally 140 µg/l to 6.2 – 8.6 µg/l, which still lies under the WHO guideline value. This is a reduction of 94 – 96%.

What has to be considered is that the fogwater was in contact with the pure CaCO_3 for 48 hours. Also, these experiments were conducted under laboratory conditions. The CaCO_3 was in powdery form and was mixed evenly with the water. For treating the fogwater the CaCO_3 should rather be in granular form embedded in a sand filter. Otherwise the water has to be mixed constantly with CaCO_3 . High amounts of CaCO_3 would have to be used and the particles would have to be removed by sedimentation and filtration after its reaction with the water.

After the mixing of the water with the technical CaCO_3 very small magnetic metallic flakes accumulated on the magnetic stirrer (see figure 44). This suggests a precipitation of the trace metals iron, cobalt, and nickel by the technical CaCO_3 (www.quantenwelt.de). This precipitation could not be observed with the pure CaCO_3 .



Fig. 44: Magnetic stirrer with metallic accumulation

The filter consisting of iron oxide and charcoal was not as effective as the CaCO_3 . Only a slight reduction of the arsenic concentration can be observed. In two cases (first 100 g/l and first 150 g/l) the concentrations even increased. These two cases were the first time the filter was used. As explained above, the water with 50 g/l CaCO_3 was filtered in the filter for water with 150 g/l CaCO_3 after the filtration of this water. Even though the filters were rinsed before their usage with the contaminated water, some arsenic concentrations in the substances of the layers, probable the charcoal, must have still been existing and were leached out.

4.3 Possible Treatment System

The first flush system for the removal of the initial water collected in a fog event is introduced in this chapter. As the initial water has higher concentrations, its separation should be taken into consideration. Also a proposition for filtration with CaCO_3 , based on the results of the experiments with the fogwater collected in Alto Patache, is given.

4.3.1 First Flush

The highest ion concentrations in the water gained through the fog collectors are to be found in the beginning of a fog event. Deposition of dust and aerosols accumulates on the nets of the fog collectors in between fog events and is then washed off by the fog water at the beginning of the fog event. Also, the first fog of a fog event scavenges more aerosols out of the air than later fog.

Through a first flush system, the first water with high chemical concentrations obtained in a fog event is diverted before it reaches the collection tank. This prevents the mixing of the first water with the water obtained later on during the fog event with lower chemical concentrations and can lower the concentrations in the collection tanks significantly.

The diversion of the first water collected should be done for an adequate period of time until the nets are clean. Hereby the volume of lost water through diversion and high concentrations of constituents in the collected water prior to further treatment has to be balanced.

The diversion can be done manually during every fog event by either moving the pipe so the first flush does not flow into the water tank or by installing a valve or plug, which is to be closed after every first flush (www.rainwaterharvesting.org). But this requires that somebody is in charge doing this every day of a fog event. As fog collectors are mostly outside of communities in remote areas this is not feasible.

A practicable system, which runs without continuous supervision, can be easily built using PVC pipes. A standpipe is connected to the water pipe with a T-fitting so the water flows into the standpipe instead of the collection tank. When the standpipe is full the water continues to flow to the collection tank (see figure 45). This system can also be enhanced by integrating a ball valve consisting of a ping-pong ball and diminution of the pipe on the upper end (see figure 46). When the pipe is full from the diverted first flush the ball seals the standpipe preventing the mixing of the clean water and the first flush. (TWDB 2005)

But under a flow rate of 3.03 l/min the water in the standpipe is almost not influenced by the water passing over the first flush system (Mechell 2009) and therefore a ball valve is only improving the system above a flow rate of 3.03 l/min.

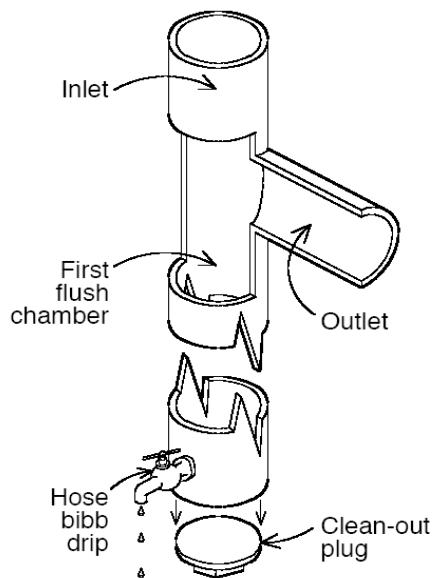


Fig. 45: First flush system without floating ball (TWDB 2005)

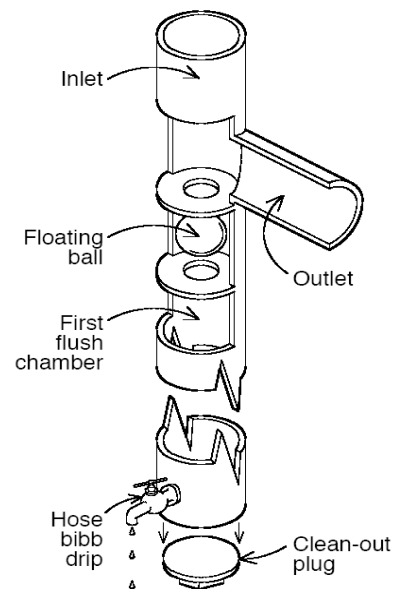


Fig. 46: First flush system with floating ball (TWDB 2005)

By inserting a drain on the bottom of the standpipe, the system can drain by itself in between fog events so the standpipe is empty before the next fog event begins. The drain can be an almost closed valve or a pinhole (TWDB 2005). What has to be taken into consideration is that the flow rate of the water gained through fog collectors is very low and the rate of the water draining out of the standpipe of the first flush system has to be far lower as it also drains when the first flush is over during a fog event. Otherwise the water loss through this first flush system is too high.

A dead storage to collect sediments at the bottom of the standpipe should be integrated. This has to be cleaned frequently (TWDB 2005).

4.3.2 Filtration with CaCO_3

An important part of a water treatment system for Alto Patache will be the raising of the pH. This can be achieved by bringing the water in contact with CaCO_3 . CaCO_3 can also reduce the high concentrations of arsenic found in the fogwater of Alto Patache below the WHO guideline value of 10 $\mu\text{g/l}$.

The mixing with CaCO_3 in powder form is not applicable in a large-scale on site. A constant supply of CaCO_3 would have to be ensured. Also the removal of the excess CaCO_3 and the precipitated by-products in the system would have to be guaranteed. For this a treatment step of large scale would be necessary. This can be avoided by using CaCO_3 in granular form. A multilayer filter consisting of layers of sand and CaCO_3 in granular form is a feasible method of using CaCO_3 in a water treatment system. In a multilayer filter, the lowermost layer is usually silica sand with one or several layers of media with lower specific weights above it, in this case granules of CaCO_3 . The sand layer has grain sizes of 0.4 – 0.7 mm (*Hancke 1998*). The respective lower specific weight of the granules of the next layers prevents a mixture of the layers when the filter is backwashed with water for cleaning (*Mutschmann and Stimmelmayer 2007*). The contact time of the water with the CaCO_3 granules has to be significantly higher than under the laboratory conditions of the experiments to achieve the same results. Due to the size of the granules the total contact area between water and CaCO_3 is lower and therefore a lower efficiency can be expected. Also the CaCO_3 present in the granules cannot be perfectly mixed with the water resulting in less reaction processes in some parts of the treated water. Limestone, which consists mainly of CaCO_3 , provides a low cost source for CaCO_3 in granular form and is suitable for treating water with high concentrations of heavy metals in general (*Green et al. 2006*).

The lowermost layer of sand in the multilayer filter filters the precipitations of the reactions between CaCO_3 and the concentrations in the water. After this the placement of a rapid sand filter, investigated by *Huisman and Wood (1974)*, should be taken into consideration. The rapid sand filter has granulars with diameters between 0.6 and 2 mm and a flow rate of 5 – 15 $\text{m}^3/\text{h}/\text{m}^2$. The impurities are being transported into the filter bed and deposit there on the granules. The deposition of iron and manganese is enhanced by catalytic action. A bacterial coating of the grains is achieved, but the bacterial purification is limited. Due to the larger interstices, the mechanical removal of particles is not as high as in a slow sand filter. A more thorough pre-treatment is therefore necessary. The rapid sand filter removes particles more easily in coagulated stage and is therefore also applicable after precipitation and coagulation of arsenic. The cleaning of a rapid sand filter is done by backwashing. In this process water, air, or a combination of both flows upstream through the filter and removes the coating of the granules. This has to be done every day, or every other day.

During the treatment with limestone granules armoring can develop, which is the forming of an impermeable metalhydroxide coating on the granules consisting mainly of Fe_2O_3 . Armoring is most likely to occur in solutions with high Al, Fe, and dissolved SO_4 concentrations. This coating forms around the limestone grains, inhibiting the further dissolution of CaCO_3 to the water to be treated. Also the formation of gypsum ($\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$) coating around calcite grains can occur. This layer forms between the outer surface of the grain and the metalhydroxide coating and its formation is enhanced by higher Ca and SO_4 concentrations. Gypsum can also hinder the dissolution of calcite. The metalhydroxide coating can be mechanically removed from

the grains as it is very soft in comparison with the hardness of calcite grains. The formation of gypsum is slowed down in oxic limestone drains. In this environment the CaCO_3 rather continues to dissolve than to precipitate hindering the gypsum from forming (*Cravotta and Trahan 1999*; cited by *Hammarstrom et al. 2003*). Also high CO_2 concentrations enhancing the dissolution of CaCO_3 can prevent the formation of armoring and gypsum (*Hammarstrom et al. 2003*).

If the treated water is not consumed immediately, it has to be stabilized prior to the distribution with metal piping. If it will be in contact with metal piping in the distribution system, corrosion is very likely and the pH will drop again, as the buffering capacity is low. Raising the hydrogen carbonate concentration in the water increases the buffering capacity. This can be achieved by adding sodium hydroxide (NaOH) solution, sodium carbonate (Na_2CO_3), or sodium hydrogen carbonate (NaHCO_3). The addition of inhibitors in form of phosphates, silicates, or a phosphate silicate mixture also leads to a stabilization and inhibits corrosion (*Nissing 2004*).

Disinfection prior to consumption should also be taken into consideration.

Building a multilayer filter with charcoal, as described in chapter 4.2.1.3, is not recommended if the filter is not regularly maintained. Charcoal, providing a cheap alternative to activated carbon, can become a medium on which bacterial growth is accelerated, if the charcoal is not frequently renewed or the filter is not being used for some time. The result is a higher bacteria count in the filtered water compared to the raw water (*Heber 1985*).

5 Summary and Conclusions

Atrapanieblas are an ideal technique for small-scale water supply in warm climates. The specific environment with high frequencies of fog events needed for atrapanieblas can be found all around the world. As most of these environments are in arid and semiarid climates where water is scarce, atrapanieblas are a good alternative water source in these regions. Humans already used techniques to win water out of the atmosphere in arid regions in ancient times. Unfortunately, these techniques are mostly forgotten today. Atrapanieblas however, first investigated in 1954, present a good modern alternative.

The ideal environments providing thick fogs needed for collecting the fogwater with atrapanieblas can be found in warm climates at low latitudes. As these environments are linked to topographic conditions, and global and local weather systems and weather phenomena which are consistent and occur periodically, possible sites for fog collectors can be predicted quite accurately. The weather phenomena with the best regular conditions for fog harvesting are the trade inversions in the eastern Atlantic and Pacific Ocean at low latitudes north and south of the equator. These cause regular fog events and low level stratiform clouds, which are pushed onshore by the sea breeze where the fogwater can be collected with atrapanieblas.

However, the fogwater collected by atrapanieblas may not be drinking water according to the drinking water guidelines of the *WHO*. The factors responsible for poor water quality are both natural and anthropogenic. Due to their physical and chemical properties, fog and cloud droplets take up aerosols with their chemical constituents and produce acids in chemical processes. The aerosols are often produced in industrial processes or have other anthropogenic sources, but also dimethylsulfide produced naturally in oceans can lower the pH in the fogwater. These influences result in low pH and high concentrations of trace metals, which affect the health of consumers negatively. Therefore a treatment prior to consumption is necessary. The treatment is possible with low-tech and low-cost methods.

Treating the fogwater from Alto Patache with CaCO_3 showed a twofold effect. The pH was raised and the arsenic concentration was reduced. Thus the use of CaCO_3 in the water treatment process should be considered. Using granular CaCO_3 in a multilayer sand filter is an easy to build, low-tech application. As the chemical concentrations are highest at the beginning of fog events, the implementation of a first flush system can lower the concentrations in the collection tanks considerably. The first flush system diverts the first water collected during a fog event and only directs water with lower concentrations to the water tanks.

Even though atrapanieblas need specific climatic conditions, the collection of fogwater with atrapanieblas provides an alternative water resource in regions with few or no traditional water sources. Though still not widely used, atrapanieblas have high potential for being a reliable and cheap water source in the future.

6 References

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Appendix A

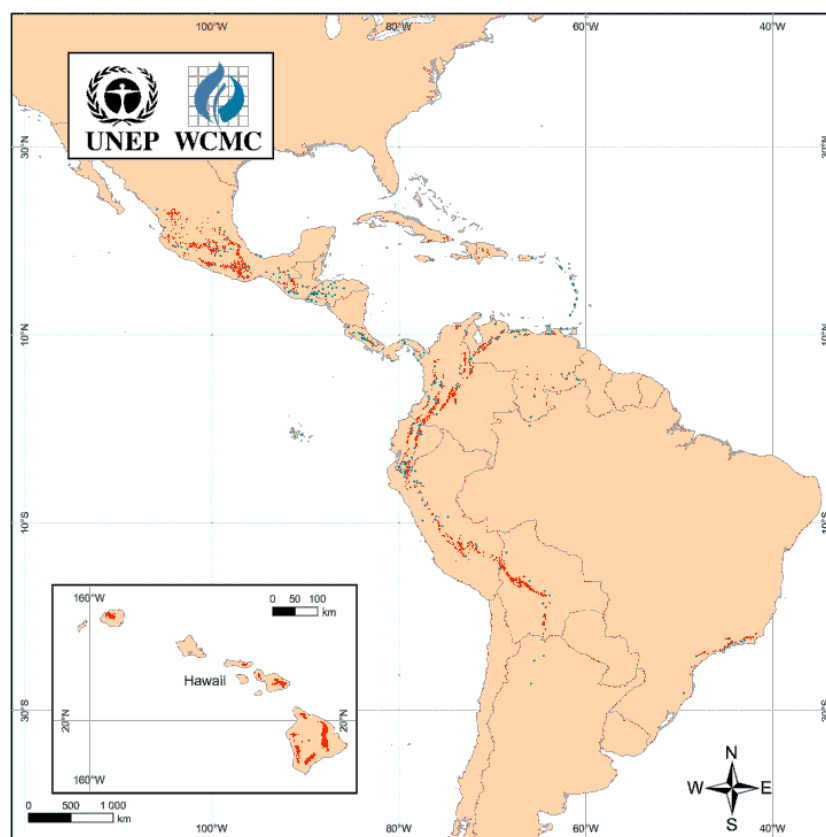


Fig. A1: Cloud forests in Central and South America (UNEP-WCMC)

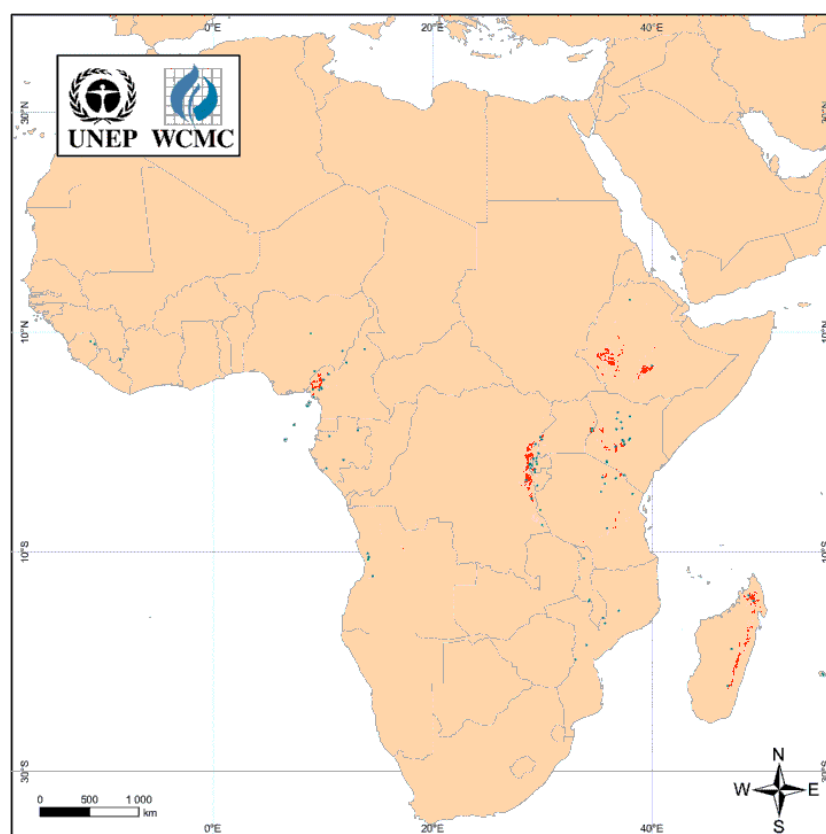


Fig. A2: Cloud forests in Africa (UNEP-WCMC)

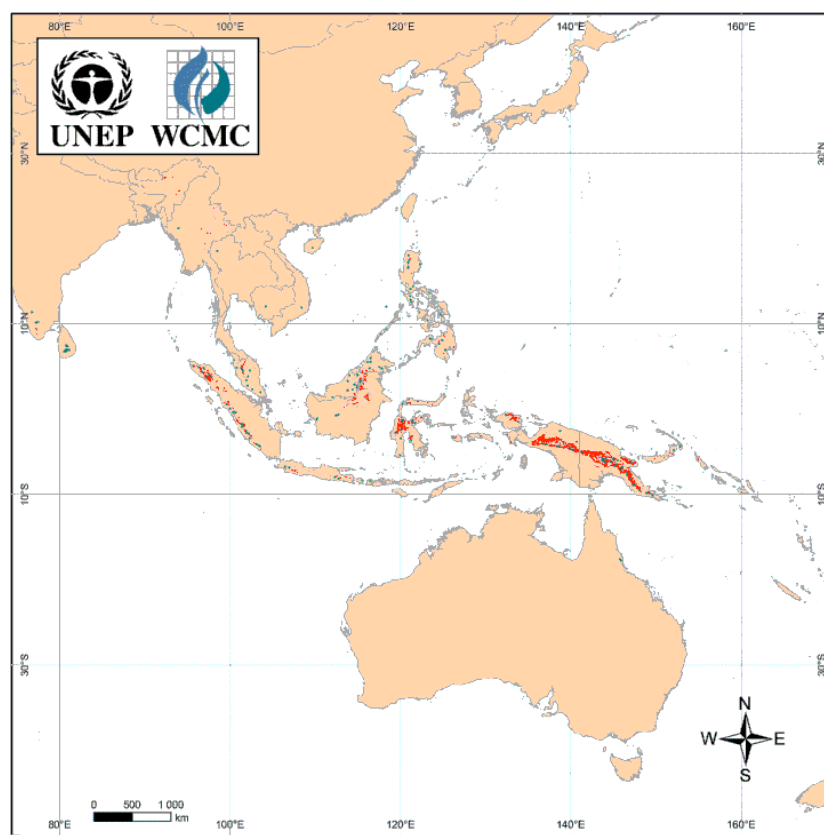


Fig. A3: Cloud forests in Southeast Asia (UNEP-WCMC)

Appendix B

Table B1: Addition of 25 g CaCO_3 to 500 ml fogwater

25g CaCO_3			
Sequence	Conductivity before CaCO_3	Conductivity after CaCO_3	°C
1	1920 $\mu\text{S/cm}$	2062 $\mu\text{S/cm}$	23.7
2	1915 $\mu\text{S/cm}$	2059 $\mu\text{S/cm}$	24.1
3	1917 $\mu\text{S/cm}$	2066 $\mu\text{S/cm}$	25.3
Time [sec]	Sequence 1 pH	Sequence 2 pH	Sequence 3 pH
0	3.25	3.23	3.24
2	3.25	3.67	3.32
4	3.30	4.20	4.04
6	3.66	5.32	5.44
8	4.53	5.83	5.96
10	4.84	6.09	
12	5.25	6.31	6.16
14	5.73	6.49	6.35
16	6.02	6.63	6.48
18	6.20	6.75	6.63
20	6.38	6.87	6.75
22	6.45	6.96	6.85
24	6.59	7.01	6.95
26		7.13	7.04
28	6.81	7.20	7.12
30	6.91	7.26	7.19
32	7.04	7.32	7.26
34	7.15	7.37	7.31
36		7.42	7.37
38	7.26	7.46	7.41
40	7.35	7.49	7.43
42		7.53	7.50
44	7.44	7.55	7.52
46	7.46	7.58	7.55
48	7.52	7.59	7.58
50	7.55	7.64	7.60
55		7.68	7.67
60	7.67	7.72	7.72
65	7.71	7.76	7.75
70	7.74	7.79	7.79
75	7.77	7.82	7.82
80	7.81	7.84	7.84
85	7.83	7.86	7.86
90	7.86	7.88	7.88
105	7.91	7.93	7.93
120	7.95	7.96	7.96
135	7.98	7.99	7.99
150	8.00	8.01	8.00
165	8.02	8.02	8.02
180	8.03	8.03	8.03
195	8.04	8.04	8.04
210	8.05	8.05	8.05
240	8.07	8.06	8.06
270	8.08	8.07	8.07
300	8.09	8.08	8.08

Table B2: Addition of 50 g CaCO_3 to 500 ml fogwater

50g CaCO_3			
Sequence	Conductivity before CaCO_3	Conductivity after CaCO_3	°C
2	1920 $\mu\text{S}/\text{cm}$	2183 $\mu\text{S}/\text{cm}$	23.5
3	1915 $\mu\text{S}/\text{cm}$	2190 $\mu\text{S}/\text{cm}$	25.2
Time [sec]	Sequence 2 pH	Sequence 3 pH	
0	3.26	3.26	
2	3.93	3.30	
4	4.20	3.49	
6	4.78	5.44	
8	4.98	5.80	
10	5.30	6.26	
12	5.64	6.60	
14	5.74	6.69	
16	5.95	6.80	
18	6.18	6.91	
20	6.39	7.03	
22	6.55	7.09	
24	6.94	7.19	
26	6.99	7.28	
28	7.20	7.35	
30	7.39	7.46	
32	7.46	7.49	
34	7.48	7.54	
36	7.52	7.58	
38	7.57	7.61	
40	7.60	7.65	
42	7.65	7.67	
44	7.68	7.69	
46	7.70	7.72	
48	7.73	7.74	
50	7.75	7.76	
55	7.85	7.79	
60	7.95	7.80	
65	8.00	7.82	
70	8.00	7.85	
75	8.00	7.89	
80	8.00	7.90	
85	8.01	7.92	
90	8.01	7.93	
105	8.02	7.96	
120	8.02	7.98	
135	8.02	8.00	
150	8.02	8.01	
165	8.05	8.02	
180	8.05	8.03	
195	8.06	8.04	
210	8.06	8.05	
240	8.09	8.06	
270	8.09	8.07	
300	8.10	8.07	

Table B3: Addition of 75 g CaCO₃ to 500 ml fogwater

75g CaCO ₃			
Sequence	Conductivity before CaCO ₃	Conductivity after CaCO ₃	°C
1	1928 µS/cm	2313 µS/cm	20.5
2	1921 µS/cm	2289 µS/cm	20.3
3	1916 µS/cm	2285 µS/cm	20.0
Time [sec]	Sequence 1 pH	Sequence 2 pH	Sequence 3 pH
0	3.28	3.29	3.28
2		3.69	3.71
4		4.95	4.37
6		5.10	5.25
8		6.16	5.90
10		6.32	6.24
12	6.49	6.53	6.55
14	6.59	6.63	6.67
16	6.68		6.95
18	6.78		7.09
20	6.95	7.01	7.21
22		7.16	7.26
24	7.06 [25 sec]	7.24	7.35
26		7.31	7.42
28		7.35	7.48
30	7.15	7.43	7.53
32		7.48	7.57
34		7.53	7.61
36		7.56	7.64
38		7.59	7.67
40		7.63	7.69
42			
44	7.63 [45 sec]	7.69 [45 sec]	7.73
46			7.76
48			7.77
50		7.74	7.78
55		7.77	7.81
60	7.80	7.80	7.83
65		7.83	7.85
70		7.86	7.87
75		7.87	7.88
80		7.89	7.89
85		7.90	7.90
90	7.89	7.92	7.91
105		7.95	7.93
120	7.96	7.97	7.95
135		7.98	7.97
150	7.99	8.00	7.98
165			7.99
180	8.01	8.02	7.99
195			8.00
210	8.03	8.03	8.00
240	8.04	8.04	8.01
270	8.05	8.05	8.02
300	8.06	8.05	8.02

Appendix C

Table C1: Water yield in Alto Patache (according to CDA)

Month	I/m²	I/m²/day
<i>Jan 03</i>	99.69	3.22
<i>Feb 03</i>	14.09	0.50
<i>Mar 03</i>	22.23	0.72
<i>Apr 03</i>	54.91	1.83
<i>May 03</i>	335.06	10.81
<i>Jun 03</i>	250.82	8.36
<i>Jul 03</i>	402.64	12.99
<i>Aug 03</i>	376.14	12.13
<i>Sep 03</i>	603.47	20.12
<i>Oct 03</i>	219.51	7.08
<i>Nov 03</i>	238.30	7.94
<i>Dec 03</i>	46.55	1.50
<i>Jan 04</i>	24.78	0.80
<i>Feb 04</i>	34.37	1.23
<i>Mar 04</i>	11.46	0.37
<i>Apr 04</i>	47.21	1.57
<i>May 04</i>	64.35	2.08
<i>Jun 04</i>	171.60	5.72
<i>Jul 04</i>	293.69	9.47
<i>Aug 04</i>	493.75	15.93
<i>Sep 04</i>	409.34	13.64
<i>Oct 04</i>	434.37	14.01
<i>Nov 04</i>	144.48	4.82
<i>Dec 04</i>	48.59	1.57