Master´s Thesis

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Sustainability of Rainwater Harvesting Systems Used for Gardening in the Context of Climate Change and IWRM.

An example from the Cuvelai-Etosha Basin in Namibia.

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I Abstract English

In situ rainwater harvesting has a long history in arid and semi-arid regions of the world buffering water shortages for human consumption and agriculture. In the context of an Integrated Water Resource Management (IWRM) in the Cuvelai Basin in northern Namibia, roof top rainwater harvesting is being introduced to a rural community for the irrigation of household scale gardens for the cultivation of horticulture products. This study elaborates how harvested rainwater can be used for garden irrigation in a sustainable manner evaluating ecologic, economic and social implications. Considering local conditions eight cropping scenarios were designed, including different criteria as well as one and two annual planting seasons. These schemes were tested under present climate conditions and under three future climate change scenarios for 2050 with the help of a tank model designed to model monthly tank inflows and outflows. Special attention was laid on risk and uncertainty aspects of varying inter-annual and inter-seasonal precipitation and future climate change. A framework for the assessment of sustainability was adapted to the purposes of this study and indicators have been developed in order to assess the cropping and irrigation schemes for sustainability.

The study found that with the given tank size of 30 m³, depending on crop scenario, under optimized conditions a garden area of 60 to 90 m³ can be irrigated. The choice of crops highly impacts water use efficiency and economic profitability, compared to the considerably lower impact of amount of annual planting seasons and future climate change. In the case of worsening future climate conditions, adaptation measures need to be taken as especially the economic as well as the environmental situation are expected to exacerbate due to expected decreases in yields and revenues. Already under present conditions however, the economic dimension represents the most limiting factor to sustainability, particularly due to the excessive investment costs of the rainwater harvesting and gardening facility. Nonetheless, rainwater harvesting in combination with gardening can be regarded as successful in securing household nutrition, providing sufficient horticulture products for household consumption or market sale. At the same time with the optimal choice of crops the investment costs can be recovered within the end of the lifespan of the facility.

II Abstract German

In situ Regenwassersammlung hat in ariden und semi-ariden Gebieten der Welt eine lange Geschichte und dient bei Wasserknappheit als Puffer für den menschlichen und landwirtschaftlichen Verbrauch. Im Rahmen eines Integrierten Wasser Ressourcen Managements (IWRM) im Cuvelai Becken im nördlichen Namibia, wurde die Dachregenwassersammlung in einer ländlichen Gemeinschaft zur Bewässerung von Gärten auf Haushaltsebene zwecks des Anbaus von Gartenprodukten eingeführt. Diese Studie erörtert wie gesammeltes Regenwasser für die Bewässerung von Gärten nachhaltig eingesetzt werden kann und evaluiert die ökologischen, ökonomischen und sozialen Auswirkungen. Unter der Berücksichtigung von lokalen Gegebenheiten wurden acht Anbau- und Bewässerungspläne aufgestellt, die verschiedene Anbaukriterien sowie eine und zwei jährliche Anpflanzungszeiten beinhalten. Diese Pläne wurden unter heutigen Klimabedingungen sowie unter drei zukünftigen Klimaszenarien für 2050 mit Hilfe eines Tankmodels getestet, das dazu entworfen wurde monatliche Tank Zu- und Abflüsse zu modellieren. Besonders beachtet wurden dabei Risiko und Unsicherheitsaspekte von schwankenden jährlichen und saisonalen Niederschlägen und zukünftige Klimaveränderung. Ein Rahmen für die Nachhaltigkeitsbewertung wurde für diese Studie angepasst und Indikatoren wurden für die Bewertung der Anbau- und Bewässerungspläne entwickelt.

Die Studie hat befunden, dass mit der gegebenen Tankgröße von 30 m³, je nach Anbauszenario, eine Gartenfläche von 60 bis 90 m² bewässert werden kann. Die Auswahl der Feldfrüchte hat dabei maßgebliche Auswirkung auf die Wassernutzungseffizienz und auf die ökonomische Wirtschaftlichkeit, verglichen mit der relativ geringeren Auswirkung der Anzahl der jährlichen Anbauperioden und des zukünftigen Klimawandels. Im Falle einer Verschlechterung zukünftiger Klimabedingungen, müssten Anpassungsmaßnahmen ergriffen werden, besonders hinsichtlich der zu erwartenden Verschärfung der ökonomischen aber auch der ökologischen Situation, da niedrigere Ernteerträge und Einnahmen zu erwarten sind. Schon unter jetzigen Klimabedingungen, stellt die ökonomische Dimension die größte Nachhaltigkeitsbeschränkung dar, vor allem durch die sehr hohen Investitionskosten für die Regenwassersammel- und Gartenanlage. Nichtdestotrotz, kann Gartenanbau in Kombination mit Regenwassersammlung als erfolgreich für die Nahrungssicherung auf Haushaltsebene eingestuft werden, da genügend Gemüse und Obstprodukte für den Haushaltsverbrauch oder den Marktverkauf produziert werden können. Gleichzeitig können die Investitionskosten innerhalb der Lebensdauer einer Regenwassersammelanlage, bei optimaler Auswahl der Feldfrüchte, erwirtschaftet werden.

III List of symbols and abbreviations

°C	Degrees Celsius
CO_2-eq.	Carbon dioxide equivalents
°E	Degrees East
€	Euro
FAO	Food and Agricultural Organization of the United Nations
f	following page
GDP	Gross Domestic Product
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
km^2	Square kilometers
l	Liters
MJ	Mega joules
mm	Milli meters
m	Meters
m^2	Square meters
m^3	Cubic meters
mm/a	Millimeters per annum
N$	Namibian Dollar
Rs	Indian Rupee
°S	Degrees South
UNDP	United Nations Development Program
US$	United States of America Dollar
USDA S.C.	United States Department of Agriculture Soil Conservation Service Method
w.y.	Source without indication of year

1 Introduction

1.1 Background

The achievement of all Millennium Development Goals (MDGs), adopted by Heads of State in the year 2000, depends on the availability of water in acceptable quality and adequate quantities. While access to safe water is a specific target of Millennium Goal 7, it is predicted that by 2025 one-third of the population in developing countries will face water scarcity, with severe water deficits being experienced in arid and semi-arid regions (Khaka et al. w.y.: 3, GWP TEC w.y.: 1).

The concept of “Integrated Water Resources Management” (IWRM) has become an internationally recognized paradigm in water policy during the past years (Dölle et al. 2006: 9). IWRM promotes the “coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.” (GWP TAC 2000: 22). The approach has been influenced by the Dublin Principles and discussions held during the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992 (GWP 2000: 13ff). The concept is of particular significance for arid and semi-arid regions facing water scarcity and increased pressure on water resources, but also for other regions, such as the European Union that anchored the concept in its Water Framework Directive.

As part of a process towards the development and implementation of an Integrated Water Resources Management (IWRM) in the Cuvelai-Etosha Basin the research project CuveWaters aims at improving people’s living conditions and livelihoods by introducing alternative water technologies and practices. The project operates in the Cuvelai Basin and currently focuses on the Namibian part, which is named the Cuvelai-Etosha Basin (Deffner et al. 2008: 7). Project implementation is conditioned by the IWRM approach and the Dublin Principles which encompass a holistic and long-term view on the entire system and is dedicated to sustainability.

The objective of the project is to reduce dependency on water from the Kunene River as well as to improve water supply security, use efficiency and quality for villages by the installation of different decentralized supply systems. The project focuses particularly on more efficient and intensive use of local water resources in order to create a multi-resources mix, which helps to allocate water of differing qualities from different sources for differing purposes, while increasing water productivity through water re-use and waste water recycling. A mix of different technologies is envisaged that link water use with other aspects such as use of rangelands, agriculture, wastewater management and pollution control (Deffner et al. 2008: 7, Lux et al. 2009: 7). Identified technologies are rainwater harvesting, decentralized solar desalination plants, artificial groundwater recharge and waste water reuse (Sturm et al. 2009: 777). Further project components are stakeholder and specifically community participation, concept research, empirical work, good governance, institutionalization and capacity building (Deffner et al. 2008: 7).

CuveWaters is funded by the German Federal Ministry of Education and Research (BMBF) and implemented through a research cooperation of the Institute for Social-Ecological Research (ISOE), the Technical University Darmstadt (Chair of Water Supply and Groundwater Protection and Chair of Wastewater Technology). In Namibia, CuveWaters cooperates closely with the Ministry of Agriculture, Water and Forestry (MAWF), the Desert Research Foundation of Namibia (DRFN), the Federal Institute for Geosciences and Natural Resources (BGR), the German Technical Development Cooperation (GTZ) as well as local and regional institutions and authorities (Deffner et al. 2008: 7, Lux et al. 2009: 7).

The project is structured in three phases: The initial phase aimed at preparing the conceptual base of the project (November 2006 to April 2009), while the current second phase, the pilot phase (June 2009 to 2013) will focus on the integration and implementation of technologies with further adjustments, monitoring and evaluation. A third phase is planned (2013 to 2015), with the spotlight on the broad diffusion of the tried and proven technical systems while strengthening corresponding structures and building up expertise (CuveWaters 2008a: 2, CuveWaters 2008b: 10).

1.2 Objective of the study

The objective of the study is to elaborate how rainwater harvesting systems can be used at the household scale for the irrigation of gardens in a sustainable manner. For this purpose an appropriate cropping and irrigation scheme that optimizes water use will be elaborated, considering local conditions and future impacts of climate change. It could be part of a broader management scheme which would also incorporate aspects of responsibility or institutional structures. These aspects however lay outside of the scope of this study. Special attention will be put on risk and uncertainty aspects concerning varying inter-annual and inter-seasonal precipitation and future climate change. Indicators will be developed in order to assess the cropping and irrigation schemes for sustainability.

1.3 Methodology

Available climate data from the National Weather Bureau of Namibia is going to be analyzed, having a closer look on seasonal and annual rainfall variability. Research will be done through internet and library research as well as project documents review. A rainwater harvesting tank model will be set up and different crop scenarios and climate scenarios will be defined. Crop water and irrigation requirements will be calculated using a tool and the procedure suggested by the Food and Agricultural Organization of the United Nations (FAO). Climate scenarios will be modeled with data from the Intergovernmental Panel on Climate Change (IPCC). Each cropping and irrigation scheme will be modeled under present climate and future climate conditions in the year

2050. These schemes will be assessed for sustainability, through the creation of a framework for sustainability assessment adapted for this study. Indicators covering the disciplines ecology, economics and social science will be defined in order to assess sustainability of the cropping and irrigation schemes.

1.4 Structure of the study

The study starts with an introduction including background, objectives and purpose as well as methods of the study. The second chapter outlines basic concepts for the study such as rainwater harvesting and sustainability assessment. Then, the third chapter presents the case study region Namibia; the country's background situation, climate change projections, rainwater harvesting and urban gardening in Namibia. In the fourth chapter the procedure of the study, methods and data used are presented. Later, beginning with chapter 5 and the presentation of the rainwater harvesting model, the results of the study are presented. Subsequently the ecologic, economic and social implications of the study region are analyzed, followed by the creation of cropping and irrigation schemes for rainwater harvesting in combination with gardening. Afterwards, the results of the study will be discussed, followed by the conclusion.

2 Basic Concepts

2.1 Rainwater harvesting

2.1.1 Overview of rainwater harvesting

„Rainwater harvesting consists of a wide range of technologies used to collect, store and provide water with the particular aim of meeting demand for water by humans and/ or human activities.” (Barron et al. 2009: 9). Increased water provisioning capacity at a specific location enables management and use of water for multiple purposes in order to bridge dry spells and droughts (Barron et al. 2009: IX).

The art of rainwater harvesting has been probably developed around 4500 BC (Li et al 2000: 477) and practiced since the first human settlements. Rainwater harvesting structures using cisterns are dated as early as 3000 BC in the Middle East (Barron et al. 2009: 12) while earlier rainwater harvesting systems were designed primarily to meet domestic needs for water, in recent decades many countries in Sub-Saharan Africa, the Middle East and Southeast Asia, especially India, have made efforts to develop a wide variety of techniques to collect, store and use precipitation for agricultural purposes (Li et al 2000: 477). Ever since it has been an important factor in local water management and community development, buffering supplies of rainfall to service water demand for human consumption and agriculture (Barron et al. 2009: 1, 12).

Rainwater harvesting technologies can be divided into two main types depending on the source of water collected; in situ and ex situ techniques. In situ rainwater harvesting are soil management strategies that enhance rainfall infiltration and reduce surface runoff, such as terracing, pitting or conservation tillage practices. The rainwater capture area is within the field where the crop is grown and the soil serves as capture and storage medium at the same time. Commonly in situ rainwater harvesting is implemented to counter soil erosion, to recharge soil water for crop and other vegetation grown in the landscape, or to recharge shallow groundwater aquifers for livestock and domestic use. Ex situ technologies are defined as rainwater harvesting systems with capture areas external to the point of storage. The capture area varies from being a natural soil surface with limited infiltration capacity, to an artificial surface with low or no infiltration capacity. Commonly used impermeable surfaces represent rooftops, roads and pavements (Figure 1). Storage systems are often wells, dams, ponds or cisterns (Barron et al., 2009: 10).

Many rainwater harvesting interventions to date are primarily to increase crop, fodder and timber production or to provide domestic, public as well as commercial supplies of water (Barron et al. 2009: 4). According to UNEP (Barron et al. 2009), there is no comprehensive assessment at the global level for the extent of implementation of rainwater harvesting technologies for specific uses, neither there is any summarized information on how much land is currently under rainwater harvesting. The lack of global information makes it impossible to say how many people actually benefit from rainwater harvesting at present (Barron et al. 2009: 12).

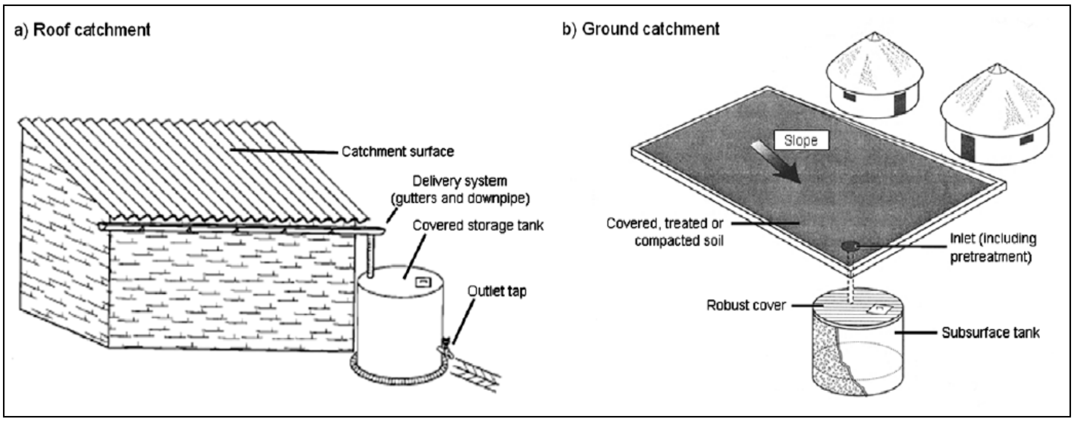


Figure 1: Schematic illustration of rainwater harvesting using roof (a) and ground (b) catchments (in Sturm et al. 2009 from Gould and Nissen-Petersen, 2003)

2.1.2 Rainwater harvesting in selected countries

The following section looks at different countries and their rainwater harvesting practices, namely China, India and Kenya. Selection criteria were developing countries, with a semi-arid climate, rainfall between 200 and 800 mm, practicing low-cost ex situ rainwater harvesting with roof and ground catchment in cisterns. However rainwater harvesting practiced in these countries differs considerably; in Gansu Province of China rainwater harvesting, mainly used for agricultural irrigation, is being promoted by government authorities through subsidies (Li et al 2000: 477) leading to huge expansion rates of the technique in only the last 20 years. In India rainwater harvesting has a great ancient tradition and is historically deeply rooted in all villages within the communities. The practice of rainwater harvesting is in decline but also seeing a revival in recent years. In Laikipia district, Kenya, rainwater harvesting is being promoted by NGOs and development organizations in recent years and now adopted successfully by communities.

2.1.2.1 Gansu Province China – a massive government program

China has a long history of rainwater harvesting techniques in many water-deficient areas dating 2000 years back, such as in the north-central province Gansu (Zhu et al. 2004: 488). Gansu, with about 31 million inhabitants (Wikipedia Gansu Province), is one of the driest, most mountainous and poorest regions in China. Average annual temperature is +6.3 °C, ranging from -27 °C to +34 °C, with 100 to 160 frost free days (Zhu et al. 2004: 489 f). Its semi-arid climate is strongly governed by monsoon rains, which are often inadequate in terms of amount and subject to high interannual and interseasonal variations (Li et al. 2000: 478, Zhu et al. 2004: 490). Mean annual precipitation is 330 mm, ranging from 500 to 600 mm in the west to 300 to 450 mm in the east (Zhu et al. 2004: 489 f) (Figure 2), while potential evaporation is as high as 1,500 to 2,000 mm (Barron 2009: 47, Zhu et al. 2004: 489 f).

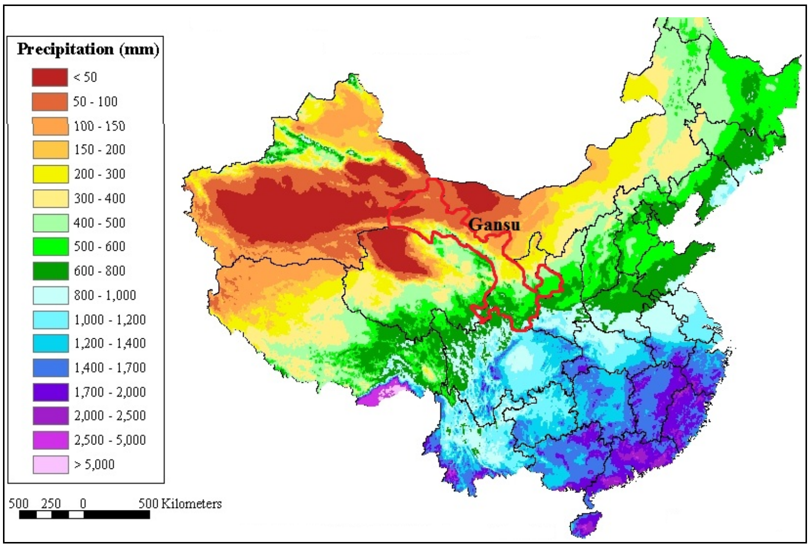


Figure 2: Mean annual precipitation in China and Gansu Province (OSU Spation Climate Analysis Service: 2002 The Climate Source, Inc. www.climatesource.com, changed)

On average 60% of the annual precipitation falls during the three summer month of July through September, often in form of heavy thunderstorms and not in accordance with the key season of crop water requirement (Li et al. 2000: 478, Zhao et al. 2009: 400). For this reason, providing supplemental irrigation to crops during their water-stress periods is essential to achieve high sustainable yields in rainfed conditions (Li et al. 2000: 478). Major problems of the region are severe seasonal drought and water shortage, low agricultural productivity, fragile ecologic environment, soil erosion and low yield-investment ratio (Zhao et al. 2009: 399f). Rain is the only water available since surface and ground water are limited and reticulated water systems are not feasible because of the terrain and the sparse population (Barron 2009: 47). Thus people generally suffer from inadequate supplies of drinking water and agriculture heavily relies on rainfall (UNEP web site: Rainwater harvesting and utilization).

Since the 1980s, rainwater harvesting with cistern storage has been seen as a solution to serious water scarcity with extensive research and the start of numerous projects. (Zhu et al. 2004: 488, UNEP web site: Rainwater Harvesting and Utilization). From the early 1990s rainwater harvesting systems have become a government strategy for water sector development in Gansu and in 1995/96 the Gansu Provincial government organized farmers to carry out a large rainwater harvesting project named “121 Project”. The goal was to help each farm household to build its own 100 m^2 concrete collection surface with at least two 20 – 50 m^3 storage cisterns for each acre of land issued for planting high market value cash crops such as vegetable or fruit trees. The government provided farmers with materials, whereas farmers contributed with labor. This led to a rapid expansion of rainwater harvesting in Gansu province (Li et al 2000: 477, Zhu et al. 2004: 488 f). Up to present some 2 to 2.5 million tanks with a capacity of 73.1 million m^3 were built, supplying drinking water to 2.5 million people (1.3 million according to UNEP: examples of RWH around the world, Zhu et al. 2004: 489), 1.2 million livestock (Li et al 2000: 482) and irrigation water for 270,000 ha of land (Data 2003 from Gansu Provincial Government, Lanzhou Daily 2003 in Zhu et al. 2004: 489). The rapid expansion of rainwater harvesting for both domestic and agricultural utilization has brought prosperity to the local people accelerating economic progress. Based on an investigation of the provincial government at the end of 2002 almost 225,000 farm families directly benefited from the “121 Project” as they were able to increase their annual income by 18.2 % in the past 5 years by selling agricultural products, fruits and vegetables produced using rainwater for irrigation (Gansu Daily 2003 in Zhu et al. 2004: 489).

An integrated rainwater harvesting system in Gansu usually consists of a rainwater catchment area, storage, water distribution system and agricultural facilities (Zhu et al. 2004: 493). The facilities recommended under the “121 Project” are either built by using cement paved courtyards or mortar roofs connected to a drinking water cistern for household use. Compacted land surface and hilly slopes covered with plastic film connected to a cistern surrounding or above agricultural fields or highways and roads are used for irrigation purposes (Li et al 2000: 479, Zhu et al. 2004: 493). Containers for the storage of rainwater include wells, tanks, and mini-reservoirs. In the loess area the most common storage containers represent traditional earthen or concrete wells, ideally with a cover to prevent evaporation loss. Research suggests that the optimal volume for a concrete tank is 30 to 50m³ (Li et al 2000: 479). Greenhouses for vegetable cultivation, where the plastic roof can also serve as collection surface, are widely used to attain the highest benefit from rainwater harvesting. Effective water-saving systems such as low-cost mobile and semi-fixed micro-drip irrigation systems that are suitable for small-scale farmers are crucial for the economical and effective use of water (Li et al 2000: 479). According to Zhu et al. (2004: 495) the basic cost of a cistern with a volume of 30 to 50 m³ in Gansu is 120 to 160 US$, excluding labor costs. Li et al. (2000: 480) indicate average costs of 125 US$ for a 30 m³ concrete well including construction, material and labor costs.

Rainwater harvesting played a significant role in promoting ecological and environmental conservation (Barron 2009: 47). Other advantages of rainwater harvesting systems in Gansu are high water quality if collected from roof-yard systems, independence of the systems making them suitable for scattered settlement and cost effectiveness due to the use of local materials and labor during implementation. The systems are suited at a convenient distance from the households and provide water at the point of consumption. Households have full control of their own systems, which greatly reduces operation and maintenance problems and farmers have a greater incentive to maintain them. They are easy to construct, do not require long construction delays and can provide benefits in the same year of construction, investments are relative low and affordable for farmers in poor areas (Li et al 2000: 478 f, Zhu et al. 2004: 491, 493,). Disadvantages of rainwater harvesting technologies are mainly due to the limited supply and uncertainty of rainfall (Zhu et al. 2004: 493).

The success of rainwater harvesting for domestic water supply, rain-fed agriculture, drought mitigation and improvement of the ecosystem in Gansu has spread rapidly to other semi-arid, drought prone and sub-humid regions of China, such as Southwest

China, the coastal towns of Southeast China, the islands and Guangxi Autonomous Region where similar programs have been started (Li et al 2000: 482, Barron 2009: 48). Up to now seventeen provinces in China have adopted rainwater harvesting, building 5.6 million tanks with a total capacity of 1.8 billion m^3, supplying drinking water for approximately 15 million people and supplemental irrigation for 1.2 million ha of land (UNEP web site: Rainwater harvesting and utilization).

2.1.2.2 The Thar Desert in northwestern India – an ancient tradition in decline

In India rainwater harvesting as an adapting strategy to optimize the availability of water has a history of continuous practice for at least the last 8000 years (Pandey et al. 2003: 48, 55). Its first origins where simplest earthworks in the Thar desert in Rajasthan. Rainwater harvesting was used ever since all over India as a response to climate extremes and climate change as the monsoon rains fluctuated over decades (Pandey et al. 2003: 56). It is estimated that today traditional village tanks, ponds and earthen embankments number more than 1.5 million and harvest water in 660,000 villages in India (Pandey et al. 2003: 53).

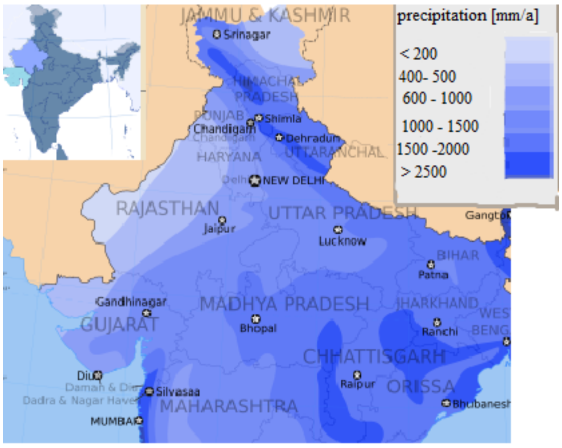


Figure 3: Annual mean precipitation in northwestern India (Wikipedia.org India annual rainfall map, changed)

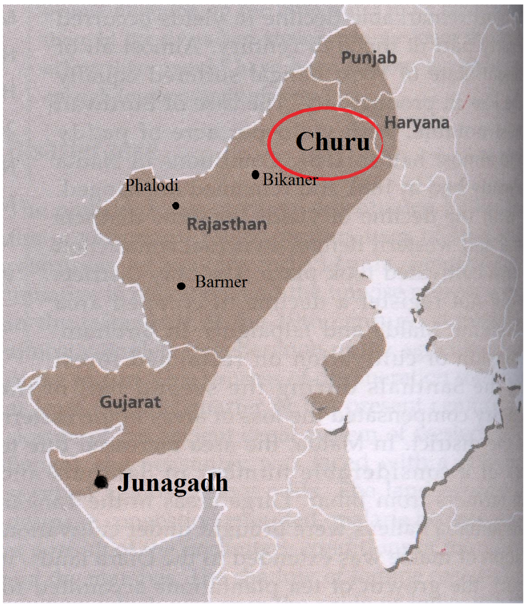


Figure 4: Thar desert with Churu province and several cities in northwestern India (Agarwal and Narain 2003: 104, changed)

The Thar Desert (Figure 4) covers an area of 44.6 million ha, of which 27.8 million ha lie in India, the rest in Pakistan. In India most of the desert is suited in western Rajasthan and northeastern Gujarat. The west is classified as arid, with about 100 mm mean annual rainfall, and the east as semi-arid, with 500 mm rainfall with high interannual variability (Figure 3) (Agarwal et al. 2001: xvi, Wikipedia.org, Climate of India). The region is characterized by a lack of water resources, since there are no rivers and groundwater is saline. Nearly 60% of the Thar is farmed with varying intensities of crops, while 30% are pastured. Agriculture in the region is extremely precarious. On average droughts occur 4 out of 10 years and land use is largely dependent on rainfall.

As rainfall in the Thar is very erratic, rainwater harvesting is deeply rooted in its social fabric (Agarwal and Narain 2003: 104 f). Particularly prevalent as source of water are *tankas* and *kunds* (Agarwal and Narain 2003: 129). Rooftop rainwater harvesting is common across all villages and towns of the Thar and was perfected to a fine art (Agarwal and Narain 2003: 110). Rainwater falling on roofs is directed into an underground *tanka*, a small tank, built in the main house or in the courtyard, usually as big as a room, with a volume of for example 60 m³. Formerly tankas were built in all traditional houses, such as in the desert city Bikaner, with about 550,000 inhabitants (data 2001 Indian census, Wikipedia.org, Bikaner). The collected water served exclusively for drinking purposes and was only used if all other supplies failed. Together with innumerable deep wells and tanks in the city they satisfied the city's water requirements (Agarwal and Narain 2003: 106). With average annual rainfall of 200 mm and a concrete courtyard of 100 m² area, 18 m³ of water harvested are enough to meet the annual needs of a family of 10 to 12 members. Brick tankas are also built in farmhouses, with a catchment area out of cement or clay, serving drinking water purposes. For livestock or irrigation purposes a catchment of 1 to 2 ha in and around their farms is used to collect the runoff in a farm pond (Agarwal et al. 2001: 54 f).

However, since the construction of the Rajasthan Canal, now known as the Indira Gandhi Canal, in 1958 with the aim of converting part of the Thar desert from wasteland to agriculturally productive land (Wikipedia.org, Indira Gandhi Canal, Agarwal and Narain, 2003: 133) tap water was introduced. Since then the practice of rooftop rainwater harvesting has been steadily declining and people do not feel any more the need for a traditional *tanka* (Agarwal and Narain 2003: 111). Until water was a scarce commodity it was conserved and used with utmost care and sanctity, but with the coming up of tap water, the whole concept of this scarce commodity has changed and water is often wasted. E.g. in the town of Phalodi in Rajasthan out of 40,000 houses only some 2,000 houses still maintain their *tankas*. However in recent years some households are beginning to come modern with their tankas and in arid years the tanka is filled up with tap water.

In regions not yet connected to the canal, rainwater harvesting is still practiced. Barmer is the only major town in western Rajasthan where the art of rooftop rainwater harvesting has not died out until today. A *tanka* is built before the construction of each house as it is the only assured source of sweet water.

In the sandy tracts of the Thar Desert the villagers had evolved an ingenious system of rainwater harvesting known as *kunds*, a circular covered underground tank built out of lime plaster or cement, usually between 3 to 5 m deep (Agarwal and Narain, 2003: 134). The circular catchment area, varying from 20 m² to 2 ha slopes towards the centrally located storage structure which is traditionally out of local materials such as slit, clay, lime, ash and gravel. Its catchment size can vary, depending on runoff needed and availability of spare land. A 2 ha catchment area is generally sufficient for a *kund* with a capacity of 200 m³. *Kunds* are primarily designed for harvesting drinking water (Agarwal and Narain, 2003: 127). These were usually more prevalent in the western arid regions of Rajasthan and in areas where the limited groundwater available is moderate to highly saline. In the village Jalwali near Bikaner there are for example nearly 300 *kunds*. *Kunds* were usually privately owned, the rich having several of their own. Some *kunds* were also owned by communities and built through village cooperation or by a rich man for the entire community. The first known construction in western Rajasthan was in 1607 by a Raja. Few *kunds* were built by the government during famine relief works. In the village of Jaislan two public *kunds* where built in 1988 by the government. However, maintaining these public *kunds* is a serious problem, as nobody feels responsible or motivated to clean them. Instead, it is reported that people prefer to buy water at high costs from transporters or drink saline and dirty well water.

Also in the Churu district in north-eastern Rajasthan, with a population of 1.9 million (data 2001, Wikipedia Churu district), drinking water is extremely scarce. Annual average rainfall is 350 mm occurring within 10 to 15 days in two or three thunderstorms (Agarwal and Narain, 2003: 132). Piped drinking water from the canal does not reach many villages and where pipelines exist, supply is irregular and inadequate, particularly during the summer. To deal with this situation Bhouka Charitable Trust encourages villagers to return to the traditional rainwater harvesting systems and to build or renew the *kunds* as only reliable option for quality water supply in the region. To increase runoff research projects work towards the use of new techniques such as covering the catchment area with polymer solutions. Also the rooftop is used to harvest rain into a kund. In schools located away from villages, water is made available from kunds at a much lower cost than pipeline supply. A kund of 100 m³ capacity can meet the annual drinking water requirement of a family consisting of 9 to 10 members. The *kund* also meets the drinking water consumption of 2 liters/ day of 210 school children for 240 days a year. The water is of good quality and can be drawn easily and time saving. (Agarwal et al. 2001: 68 f). A *kund* with a volume of around 25m³ costs about 12,000 Rs (200 €) (Agarwal and Narain, 2003: 132).

Also *kunds* have lost their past eminence in regions where piped water from the canal is provided. Many lie in disrepair and only few have been built over the last 10 years. Yet, because water supply from the canal is too erratic, the villagers have not given them up completely, but treat them as an alternative source of water (Agarwal and Narain, 2003: 133). Even though the government of Rajasthan had started to promote *kunds* for minor irrigation and drinking water through a subsidy from the early 1970s, it has treated them only as a supplementary source of water (Agarwal and Narain 2003: 133). To popularize *kunds*, Rathore (in Agarwal and Narain 2003: 130) suggests that the government should provide credit, particularly to poorer households, as many households do not have the means to even repair the existing ones.

In Junagadh, in southwestern Gujarat, mean annual precipitation of 300 – 500 mm is below the mean in 2 out of 3 years. During extreme water scarcity months the government has to provide drinking water through tankers to places where piped water supply does not reach. This kind of water supply is inadequate, unpredictable and at high costs, making extensive use of groundwater (Agarwal et al. 2001: 83 f). To meet water needs locally, in 1995 the Agha Khan Rural Support Program India initiated a rural drinking water program in salinity affected villages, comprised of technical, training and agriculture components. This included the construction of underground structures to harvest rainwater from rooftops for domestic consumption as well as building shallow wells. The promoted storage capacity is 20 m³, derived from the annual drinking water requirement of a family with a consumption of 7 l/day/capita. Emphasis for training was put on water quality, water storage and use. The agriculture component promoted cultivation of low water consuming, saline-tolerant crops. These facilities have been largely accepted by the community. Its costs are at average 18,000 Rs (295 €) and maintenance minimal. However, Agarwal et al. suggest that for rainwater harvested efforts so succeed, certain minimum criteria must be met; (i) the quantity of water made available through rainwater harvesting should meet basic domestic needs, (ii) the water should be potable, (iii) water sources should be dependable, protected and sustainable, (iv) control over the water harvesting system should be local, (v) economic and ecological costs for providing water should be minimal. Experiences in Junagadh show that rooftop rainwater harvesting can be a cost effective and dependable solution for water supply (Agarwal et al. 2001: 83 f).

2.1.2.3 Laikipia District in central Kenya – NGO successfully promoted programs

Although in some parts of Africa rapid expansion of rainwater harvesting systems has occurred in recent years, progress has been slower than in Southeast Asia. This is due in part to the lower rainfall and its seasonal nature, the smaller number and size of impervious roofs and the higher costs of constructing catchment systems in relation to typical household incomes. In spite of its potential, rainwater harvesting has not received adequate attention among policy makers, planners and water project managers. Nevertheless, rainwater collection is becoming more widespread in Africa with projects currently in Botswana, Togo, Mali, Malawi, South Africa, Namibia, Nigeria, Ghana, Zimbabwe, Mozambique, Sierra Leone, Ethiopia, Senegal, Uganda and Tanzania among others (Agarwal et al. 2001: 189 f, UNEP web site: Rainwater harvesting and utilization, UN News Centre 2006). Kenya however is leading the way.

Since the late 1970s, many projects have emerged in different parts of Kenya, each with their own designs and implementation strategies. These projects, in combination with the efforts of local builders operating privately and using their own indigenous designs, have been responsible for the construction of many tens of thousands of rainwater tanks throughout the country. Where cheap, abundant, locally available building materials and appropriate construction skills and experience are absent ferrocement tanks have been used for both surface and sub-surface catchment (UNEP web site: Rainwater harvesting and utilization).

In the semi-arid upper Ewaso Ng'iro river basin in Laikipia district (Ngigi et al. 2007: 129) conventional water resources such as ground or surface water are not available. Long-term annual rainfall is highly variable in spatial and temporal terms ranging from 300 to 2000 mm, with a mean of approximately 700 mm (Figure 5), with wet-dry cycles of 5 to 8 years (Gichuki 2002: 122). 30% to 40% of the rain falls from March to June and 50% to 60% of the rain from October to December. Temperature ranges from 10°C to 24 °C and mean annual potential evaporation ranges from 2000 mm to 2500 mm.

Figure 5: Rainfall in Laikipia district, Kenya (World Trade Press)

The high elevation gradient gives rise to different climatic and ecological zones, from humid moorlands and forests on slopes to arid acacia bush land in the lowlands. Despite the relatively high rainfall, its poor distribution and high potential evaporation affect the crop production in most parts of the basin (Ngigi et al. 2007: 130). Water deficit increases drastically with distance from Mt. Kenya. Local communities consist of subsistence farmers growing crops and keeping livestock. Frequent droughts result in crop failure and decimation of livestock. High population growth and conversion from semi-arid pastoral environments into agricultural lands worsen the situation and up-stream – down-stream water conflicts occur (Ngigi et al. 2007: 131). Poor distribution of water is the most limiting factor to socio-economic development in the river basin. Excess water during the rainy season is followed by severe drought during the subsequent dry season. River flow has progressively decreased by 30% since 1960 due to water abstraction increase of over 70% in the dry season. Rainwater harvesting is seen as a solution to reduce water abstractions and related conflicts as it would minimize dry season water demand (Ngigi et al. 2007: 130).

Since the 1990s individuals and institutions that are committed to increasing water supply coverage through utilization of rainwater have increased rapidly. Some have also organized themselves to better coordinate their actions, such as the Kenya Rainwater Association (KRA). To improve water availability and alleviate poverty, in 2007 the

Anglican Church of Kenya started the Laikipia rainwater project in the Laikipia district with funds from Global Environment Facility (GEF) small grants program. The project aimed to construct rainwater harvesting tanks for 4 schools and promote the planting of fruit trees and trees for timber within the school compound. Visible results were increased crop production and an improved economic situation of the people. The experience gained from the project in Laikipia has shown that increasing water supply for drinking and for food and livestock production are successful mobilization strategies for poverty alleviation. Today several small consulting firms have been set up and registered with the government. A program was introduced with an ordinary oil drum of 200 liters and a few galvanized oil sheets. Then as the success of the rooftop water harvesting spread, the size of the storage tanks increased, firstly up to 5 m^3. As awareness and, therefore, willingness to pay for increased water access improved, other tank sizes were introduced, until finally 50 to 100 m^3 tanks have been installed. The water is used for domestic and livestock requirements and for some limited vegetable growing. As a result of this, rainwater harvesting continued to impress local communities and runoff farming was introduced as well as additional other practices such as terracing, composting, afforestation and good farming practices. This has become possible as on average five hours lost earlier for fetching water now are consumed with farming. In addition, lost labor due to frequent diseases related to the use of unsafe water is now available. Moreover, there is an extra income from the excess farm produce sold and, in general, living standards have improved and poverty has been greatly reduced.

In another project in Kaijado and Lare, in the semi-arid savannah of Kenya, rainwater harvesting provides water for drinking, sanitation, and enhancing the productivity of the agro-ecosystems. The technologies introduced consisted among others of roof water harvesting for domestic purposes (drinking and sanitation) and runoff collection in ponds for small gardens. For sustainability, the project included a micro-finance component, where the community was trained to manage credits before borrowing money from commercial institutions. The project has enhanced the ecosystem functioning by recharging groundwater, increasing the volume of water stored, and reducing soil erosion through the family woodlots that reduced runoff-related erosion. Once the planted trees have matured, the women use them for fuel, contributing to the reduction of deforestation, which is a major problem in the area. Family livelihoods improved from selling vegetables and income generation activities such as bee-keeping and crafts. Since the establishment of the micro-finance component, all of the members have paid on time, and there have not been any arrears. Providing water to schools enabled girls to attend classes during their period of menstruation, thereby increasing their attendance (Barron 2009: 46f).

Experience gained in Kenya has helped build capacities of many rural and scattered communities in Uganda, Tanzania, Zimbabwe and Ethiopia. Community based institutions have been formed. This institutional arrangement provides the vehicle needed for development at the grassroots level in many developing countries. This has proved useful particularly in Kenya, where increased costs of living, collapse of several public services due to mismanagement of the resource and an inequitable distribution of resources and opportunities are rampant. Among many groups which have done rainwater harvesting, resources are better managed using local skills. As a result community knowledge and solidarity have enhanced (Agarwal et al. 2001: 191 f).

2.2 Sustainability Assessment

2.2.1 History and concept of Sustainability Assessment

Sustainability Assessment is a new and evolving concept, which is being increasingly viewed as an important tool to aid in the shift towards sustainability (Pope et al. 2004: 595). In literature, sustainability assessment is generally viewed as a tool in the 'family' of impact assessment processes, closely related to Environmental Impact Assessment and Strategic Environmental Assessment (Pope et al. 2004: 599). Sustainability Assessment is often described as "a process by which the implications of an initiative on sustainability are evaluated, where the initiative can be a proposed or existing policy, plan, program, project, piece of legislation, or a current practice or activity." (Pope et al. 2004: 595). One of the typical questions raised by sustainable assessment is how sustainability can be measured (Waheed et al. 2009: 444).

The pervasive growth of interest over the last 15 years in the idea of 'sustainability' or 'sustainable development' has brought with it challenges to the way in which impact assessment has been traditionally conceived. Designed originally in the late 1960s and early 1970s to focus on the environmental impacts of proposed projects, impact assessment has recently been reassessed to take account of the sustainable development agenda. There has been a consequent call for the development of 'sustainability assessment' procedures that would contribute to the shift towards a more sustainable society (Pope et al. 2004: 596).

Assessing sustainability firstly requires a well-defined concept of sustainability (Pearce et al. 1996: 85). Sustainable development was first described by the Brundtland Commission in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). Earlier use of the term sustainability in ecological and agricultural literature, referred to the context of productivity, either as a descriptive feature of ecosystems, "sustainability is the ability of a system to maintain productivity in spite of a major disturbance (intensive stress)" or as "sustainable yield" of agricultural crops (Conway 1983, in in Becker 1997: 2). Since the Brundtland Commission, many alternative definitions of sustainability have been proposed and diverse interpretations of the concept made. However, the meaning of sustainability is subject of intense debate among environmental and resource economists and a concept difficult to define in a way that it is meaningful and sufficiently practical to allow it to be operationalized (Ayres 1998: 1, Pope et al. 2004: 598). Many concepts of sustainability are based upon the 'three-pillar' or 'triple bottom line' (TBL) concept, which is often conceptualized as three intersecting circles representing the environment, society and the economy (Figure 6 and Figure 7) (Jörissen et al. 1999: 4, Pope et al. 2004: 599).

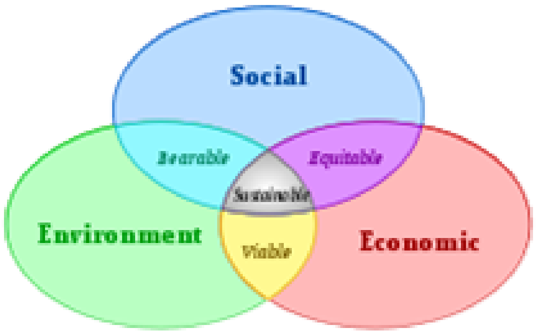


Figure 6: Three pillars of social, environmental and economic sustainability (Triple bottom line) (Wikipedia, sustainability http://en.wikipedia.org/wiki/Sustainability)

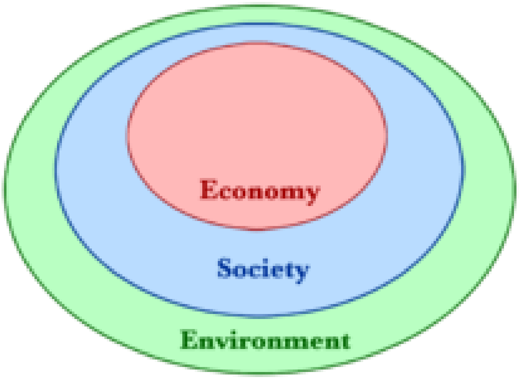


Figure 7: Concept of strong sustainability. Economy and society are constrained by environmental limits (Wikipedia, sustainability http://en.wikipedia.org/wiki/Sustainability)

Whereas the Brundtland Commission presented a two-pillar model reflecting environment and development concerns, the three-pillar TBL model separates development issues into social and economic factors, emphasizing that “material gains are not sufficient measures or preservers of human well-being” (Gibson, 2001: 7). The triple bottom line concept can be considered as an interpretation of sustainability that places equal importance on environmental, social and economic considerations in decision-making (Pope et al. 2004: 597).

The concept of sustainability can be defined as “weak” or “strong”. In case of weak sustainability, it is assumed that we can replace or duplicate natural capital such as materials and services with man-made goods and services, also known as substitutability paradigm. In case of strong sustainability it is assumed that the natural materials and services cannot be duplicated or natural capital stays constant over time. Strong sustainability is also known as non-substitutability paradigm (Figure 7). The problem with the concept of weak sustainability is that one can easily assign a monetary value to the manufactured goods, however assigning a monetary value to natural materials and services can be very difficult or impossible (Pearce et al. 1996: 85, Ayres 1998: 1, Neumayer 2003: 21, Waheed et al. 2009: 443).

The theory of Sustainability Assessment as currently expressed in the literature has largely evolved from its conceptual origins of Environmental Impact Assessment (EIA) in the early 1970s and the more recent concept of Strategic Environmental Assessment (SEA) emerged in the middle to late 1980s (Abaza et al. 2004: 7). Sustainability Assessment is often considered to be the ‘next generation’ of Environmental Assessment (Sadler 1999, in Pope et al. 2004: 598). Environmental Impact Assessment (EIA) is a typically reactive, ex-post process that aims to evaluate the environmental impacts of a policy, plan or program for which decision-making is well advanced or complete against a baseline, to evaluate the acceptability of the impacts and to identify potential modifications to improve the environmental outcomes (Devuyst 1999, Sippe 1999, Sheate et al. 2001, 2003, in Pope et al. 2004: 599). The UNEP argues that EIA is rather applied to projects while the SEA is rather applied to plans and programs (Abaza et al. 2004: 7). The International Association of Impact Assessment defines EIA as "The process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made." (Senécal 1999: 2). Its limitations are related to the late stage in decision-making processes at which EIA is applied and limited success at evaluating alternatives (Steinemann 2001, in Pope et al. 2004: 599). Consequently, Strategic Environmental Assessment (SEA) has evolved rapidly over the past decade as a series of tools for addressing the environmental implications of decisions made at much higher levels. SEA aims to be a proactive, objective- led, ex-ante process and as such it has been seen as part of the process of developing policies, plans and programs, with well-defined set of environmental objectives that describe their purpose, and promoting comprehensive analysis of alternatives (Dalal-Clayton and Sadler Dalal-Clayton and Sadler 2002, Dovers 2002, Thérivel and Partidário 1996, Partidário 1999, in Pope et al. 2004: 599).

Sustainability Assessment (SA) is a special form of integrated assessment, which takes into consideration economic, environmental and social impacts. Integration of the three pillars is often referred to as "horizontal integration" (Pope et al. 2004: 600). The term 'integration' in this sense implies that integrated assessment should be more than the sum of separate environmental, social and economic assessments. As with sustainability, the term 'integration' can be understood in different ways. The aim of integrated assessment is articulated by Post et al. (1997) as "to describe, from the perspective of an identified problem or proposed project, the relations between the human communities concerned, their economic organization and their actual resource base. It qualifies, quantifies, and, as far as possible, values the effects of proposed and alternative interventions on the three (economic, social and natural) subsystems and their intersystem relations. It attempts to identify beneficial interventions and to fully expose unavoidable trade-offs. Therefore, an integrated assessment should not only consider the environmental, social and economic implications of proposals, but should also examine the interrelations between these three pillars of the triple bottom line." (in Pope et al. 2004: 601).

2.2.2 Frameworks of Sustainability Assessment

Sustainability assessments should be applied within a structured framework (Prabhu et al. 1999: 11, Jenkins et al. 2003: 62, Pope et al. 2004: 609). A vast quantity of approaches and conceptual frameworks have been proposed and developed in various disciplines, ranging from engineering to business and policy making. A majority of these frameworks were developed in the last 10 to 20 years and did not evolve beyond the experimental stage. The main features of the conceptual frameworks include (i) setting objectives and assessment criteria based on the principles of sustainability, and (ii) defining a set of measurable indicators under each assessment criterion. The conceptual framework defines the main terms; the principles, criteria and indicators and places them in the context of sustainable management. It defines the constraints under which assessment of sustainability takes place and clarifies the hierarchical links and relationships among the different elements (Prabhu et al. 1999: 11). Sustainability Assessment frameworks help to focus and clarify what to measure, what to expect from measurement and what kind of indicators to use. They mainly differ in the way the main dimensions of sustainable development are conceptualized, dimensions are inter-linked, issues are grouped and measured, concepts are justified and finally indicators are selected and aggregated (Pinter et al. 2005: 5, Waheed et al. 2009: 448). Each of these frameworks has limited capability to deal with different issues of sustainability comprehensively and lack flexibility to be used in various disciplines with a unified interpretation (Waheed et al. 2009: 448). Based on detailed literature search Waheed et al. (2009: 448) have classified the Sustainability Assessment frameworks into following six categories: objectives based, impact based, influence based, process or stakeholder based, material flow accounting and life cycle assessment and linkages based. Waheed et al. 2009: 448) found that the majority of current frameworks are objectives-based. According to Pope et al. (2004) the two contemporary most used approaches to Sustainability Assessment are the ‘EIA-driven integrated assessment’ and the ‘objectives-led integrated assessment’.

EIA-driven integrated assessment is an impact-based framework and focuses on the impacts of various actions on the sustainability of a particular system (Waheed et al. 2009: 448). It has its origins in the 30 years of international experience with traditional, project-level EIA. Like traditional EIA, it is defined by its reactivity, and tends to be ‘applied’ after a proposal has already been conceptualized. It aims to identify whether social, environmental and economic impacts of a proposal are ‘acceptable’ compared to baseline conditions (Pope et al. 2004: 601) The focus is on minimizing negative triple bottom line impacts and consequently identifying mitigation measures through which adverse impacts might be minimized or avoided (George 2001, in Pope et al 2004.: 602). This is also often referred to as Sustainability Impact Assessment (SIA). This approach to Sustainability Assessment aims to ensure that impacts are not unacceptably negative overall, meaning that the guiding acceptability criterion for a proposal is that it does not lead to a less sustainable outcome (Neumayer 2003, in Pope et al. 2004: 604). A proposal may have positive outcomes in one dimension, but negative outcomes in the other two (Waheed et al. 2009: 448). This approach is akin to a ‘weak’ conception of sustainability, which states that as long as the overall outcome is still positive, then negative impacts in two of the categories would be acceptable. This approach can be thought of as ‘direction to target’, where the exact position of a sustainable state for that particular proposal is unknown (Figure 8). In theory it can allow for a more transparent examination of the social and economic implications of proposals. Substantive limitations of this approach are related to ‘trade-offs’ between the triple bottom line categories, conduct three separate assessment processes and the risk of economic or social requirements overriding environment standards (Pope et al. 2004: 602). To be truly integrated, the interrelations between the three pillars must be considered. Although the likelihood of win–lose scenarios can be reduced by the incorporation of minimum acceptability thresholds into the triple bottom line model and requiring that any initiative at least meets these minimum thresholds, beyond these boundaries, one set of criteria are either unduly promoted or unduly discounted against the others (Sadler, 1999, in Pope et al. 2004: 604).

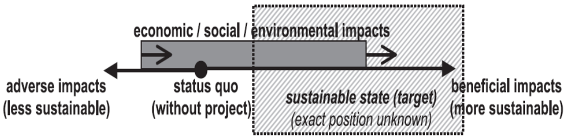


Figure 8: EIA-driven integrated assessment approach to Sustainability Assessment (minimize adverse impacts). (Pope et al. 2004: 602)

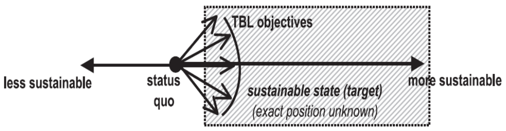


Figure 9: Objectives-led integrated assessment approach to Sustainability Assessment (maximize objectives). (Pope et al. 2004: 605)

Objectives-led integrated assessment is an objective-based framework, with origins in objectives-led SEA. This approach aims to assess the extent to which a particular initiative contributes to a defined state of sustainability, defined by integrated triple bottom line objectives (Pope et al. 2004: 605, Waheed et al. 2009: 448). This requires defining a clear state of sustainability and environmental, social and economic objectives against which the assessment can be conducted. The approach is proactive, with a ‘direction to target’ characteristic, where the position of the sustainable state is unknown (Figure 9). Pope (2004: 606) suggests that this approach is more likely to result in ‘win-win-win’ outcomes between the three pillars of sustainability and is therefore less likely to generate conflicts and trade-offs. Given the prevalent view that sustainability is about positive change rather than simply minimizing the negative, objectives-led integrated assessment clearly has more potential to contribute to sustainability than EIA-driven integrated assessment. The objectives must be consistent and compatible with each other, which in itself represents a challenging task since it is not uncommon for strategic objectives to be conflicting (Pope et al. 2004: 606).

Pope et al. (2004: 606) argue that both of these conceptions of Sustainability Assessment do not go far enough to make a significant contribution to sustainability as both can be described as ‘direction to target’ approaches. Pope et al. (2004) propose a new concept, which they call “Assessment of sustainability” that measures ‘direction to target’ as well ‘distance from target’ (Sadler 1999, Fuller 2002, in Pope et al. 2004: 609). George (2001) goes even further by stating that existing or planned proposals, initiatives, practices or activities should not be assessed for their contribution to sustainability, but determine whether or not they are, in themselves, sustainable and therefore this effectively becomes a yes/no question. Instead of only asking “Are we heading in the right direction?“ the alternative process should ask “Are we there?“

(Pope et al. 2004: 606). One of the main implications for this conception of Sustainability Assessment is that it necessarily requires a clear vision of what sustainability means, as a societal state with particular characteristics or conditions. Further, this vision needs to be translated into context specific sustainability criteria. Sustainability criteria should effectively separate sustainable outcomes from unsustainable ones for the purposes of the assessment process, which would then ask whether or not these criteria have been met (Pope et al. 2004: 609).

2.2.3 Criteria for Sustainability Assessment

There are two overarching approaches for the development of criteria for the Sustainability Assessment: the “bottom up” and the “top-down” approach. In the “bottom up” approach, such as the triple bottom line approach, objectives are defined in relation to baseline conditions. It is assumed that the state of sustainability can be defined by environmental, social, and economic objectives and criteria are developed under these categories. (Pope et al. 2004: 609, Waheed et al. 2009: 444). Problems of this approach include the challenge how to judge when extension has reached far enough to achieve the goal of sustainability. Objectives would need to define sustainability (Pope et al. 2004: 609, Waheed et al. 2009: 444). Problems arising from the separation of the holistic concept sustainability into three pillars of the triple bottom line are emphasizing potentially competing interests rather than linkages and interdependencies between pillars, making the task of integration extremely difficult and promoting trade-offs, often at the expense of the environment (Gibson, 2001, Lee 2002, Sheate et al. 2003; Jenkins et al. 2003, in Pope et al. 2004: 610).

As an alternative George (1999, 2001) and Gibson (2001) promote the use of a “top-down” approach, also called “principle-based” approach. This approach starts with the concept of sustainability as a state to which society aspires, and then moves on to define this state in terms of sustainability criteria (Pope et al. 2004: 609, Waheed et al. 2009: 444). Gibson (2001) and George (1999, 2001) argue that a principles-based approach emphasizes interconnections and interdependencies between the pillar areas rather than promoting conflicts and trade-offs and could therefore avoid some of the inherent limitations of the triple bottom line approach. An approach to Sustainability Assessment based upon fundamental principles of sustainability as defined by the Rio Declaration and Agenda 21 is recommended by several authors (Sadler 1999, George 1999, 2001, in Pope et al. 2004: 611) and by the International Association for Impact Assessment (IAIA) (Pope et al. 2004: 611). Alternative sets of sustainability principles include the Natural Step System Conditions (The Natural Step 2001; Sadler 1999, in Pope et al. 2004: 611) and the principles developed by Gibson (2001). While a triple bottom line view of sustainability could theoretically be used as a starting point to develop these criteria, in practice this is unlikely to be successful, and principles-based approaches are recommended.

2.2.4 Performance indicators

Further emphasizing the normative dimension of indicators, Parris and Kates (2003: 572) define them as ‘‘quantitative measures selected to assess progress toward or away from a stated goal’’. In order to measure the effectiveness of criteria, performance indicators are derived. They can refer to the context, conditions, means, activities or performance. Performance indicators can be single valued (i.e., derived from one variable) or composite (i.e., obtained by the aggregation of two or more variables) and be based on quantitative or qualitative performance data (Becker 1997: 21, Waheed et al. 2009: 445). Basic characteristics of performance indicators are according to Alegre (1999) as: encompassing all relevant aspects of sustainability performance, non-overlapping (i.e. mutually exclusive), easy to understand and interpret, as few in numbers as possible, verifiable, defined for a given time period and universal enough to be measured in diverse conditions (in Waheed et al. 2009: 445). Becker (1997: 20, 37) divides indicators into state and trend indicators with specific spatial scales and time horizons. Indicators can be of monetary and/ or of nonmonetary nature (Toman 1998: ii).

2.3 Relevance for the study

Revising the concept of rainwater harvesting and its use in other parts of the world with similar climates and economic conditions to those in northern Namibia gives a picture of its feasibility and potential as well as limitations and constrains. These will help to better judge the sustainability of rainwater harvesting in northern Namibia, by having an idea which criteria are relevant for success. Nevertheless, this study concentrates on the household scale and does not consider the institutional, political or macroeconomic scale. The previously presented concept of Sustainable Assessment is meant to help in the determination, whether rainwater harvesting in combination with gardening activities is sustainable in northern Namibia. The presented overview of frameworks for Sustainability Assessment will help to create an own framework suitable for the purpose of this study. The concept of sustainability underlying this study is the triple bottom line concept as it places equal importance on environmental, social and economic considerations. Through the development of indicators, sustainability is to be assessed. However, due to the limitations of this study, the Sustainability Assessment will occur in a reduced form and does not aspire to fulfill the wide range of expectations opened in the previously mentioned current debate.

3 Case study region: Namibia

3.1 Background situation in Namibia and Central Northern Namibia

3.1.1 Geography

Namibia is suited in southwest Africa, between 17° and 29° S and 11° and 26°E, on the coast of southern Africa. Neighboring countries are South Africa, Botswana, Angola and Zambia. The total land area is 824,269 km². The physical-geographic context of Namibia is determined by its position in the climatic sphere of influence of the Tropic of Capricorn and the cold Benguela Current in the Atlantic Ocean. The land surface ranges from west to east from the Namib Desert to the mountains of the continental border range with peaks up to 2,606 m above sea level. The east and the north descend into the Kalahari basin with a mean altitude of 1,000 m above sea level (Government of Namibia 2002: 1).

3.1.2 Climate

Namibia, the most arid country south of the Sahara and of the southern hemisphere, is semi-arid to hyper arid with highly erratic rainfall, ranging from over 700 mm in the northeast to below 25 mm in the southwest and west of the country. Namibia's position under the influence of the subtropical-high-pressure belt together with the cold Benguela Current along the west coast determine its main climate features (Heyns 1995: 470, Government of Namibia 2002: 1, Kluge et al. 2008: 48).

In central northern Namibia the climate is classified as semi-arid, with highly variable rainfall in spatial terms (west to east of the region) and in temporal terms (interannual and interseasonal) (Figure 10, Figure 12, Figure 13). Annual rainfall ranges from 300 mm/a in the west and from 550 to 600 mm/a in the east of the region.

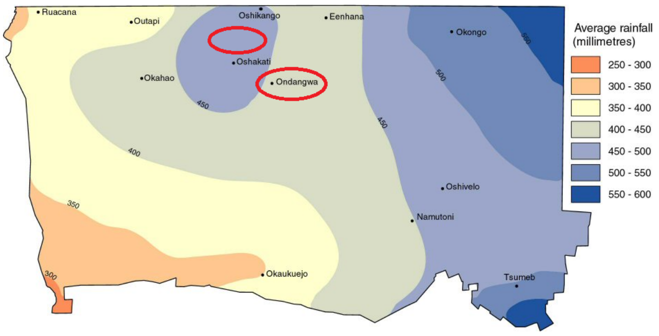


Figure 10: Annual average rainfall in Central Northern Namibia (Mendelsohn et al. 2000, with marked project location and Ondangwa meteorological station)

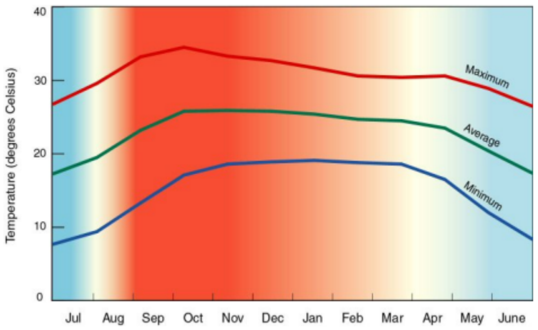


Figure 11: Temperature at Ondangwa meteorological station, Central Northern Namibia (Mendelsohn et al. 2000)

96% of annual rainfall occurs from November to April (Figure 12), the months with the highest temperatures and the highest potential evaporation rates. Average daily temperature varies between 17°C in winter and 25°C in summer (Figure 11). High solar radiation, low humidity and high temperatures lead to high potential evaporation rates of approximately 2600 mm/a (Heyns 1995: 470). Alternating droughts and floods put severe stress on the fragile ecological system and threaten the population's livelihoods (Kluge et al. 2008: 51).

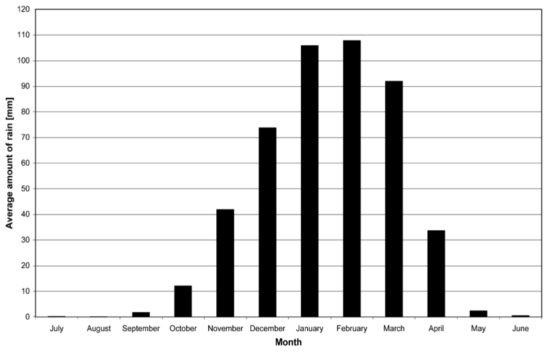


Figure 12: Seasonal rain distribution at Ondangwa station from 1902 to 1988 (Sturm et al. 2009: 779)

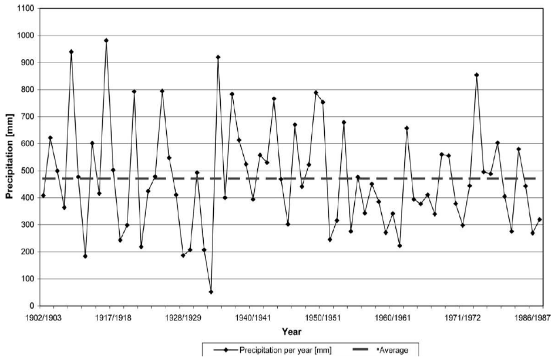


Figure 13: Annual rainfall at Ondangwa station from 1902 to 1988 (Sturm et al. 2009: 779).

3.1.3 Water resources

Namibia only has ephemeral rivers in its interior, perennial rivers exist along its northern and southern border (Figure 14) (Kluge et al. 2008: 48).

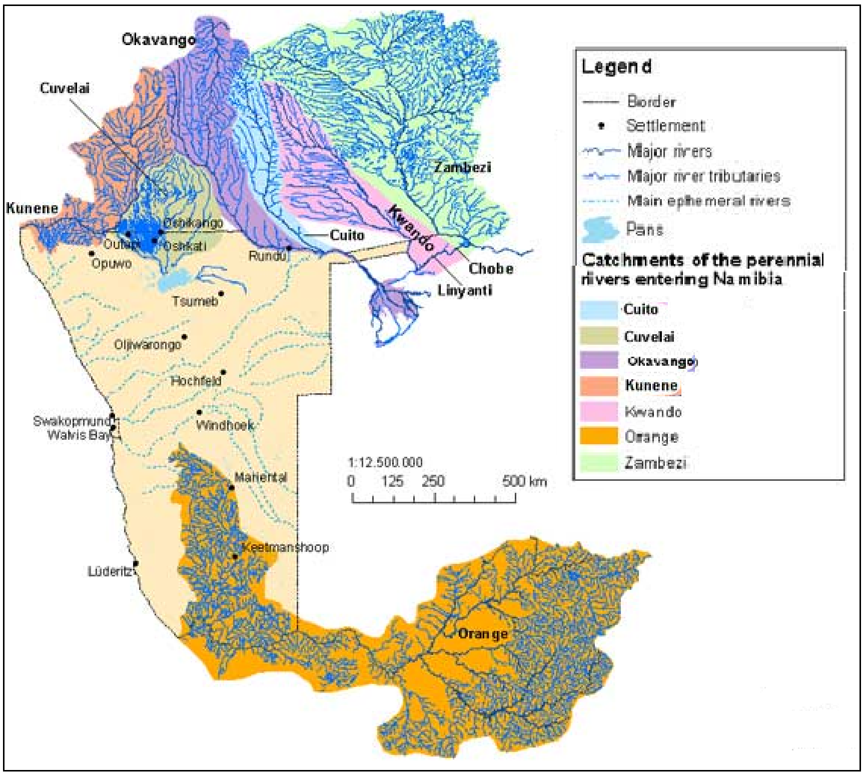
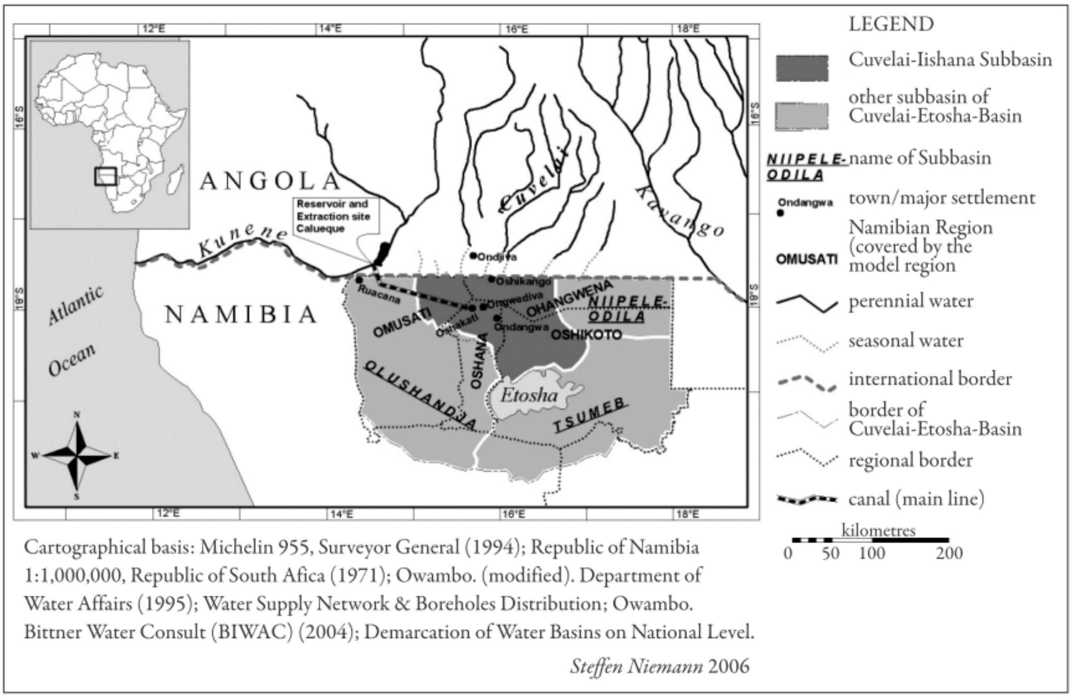


Figure 14: Perennial Rivers and the Cuvelai System (University of Cologne Acacia Project, 2004)

About 43% of the country’s water demand is supplied from surface water sources and 57% from groundwater sources which are rapidly declining. In spite of the development of new dams and pipelines water is extremely limited. Highly variable rainfall, high potential evaporation rate and increasing dependence on ephemeral surface water make water an extremely scarce resource and augment the countries vulnerability to climate change (NDP1 1995, NDP 2 2001, in Government of Namibia 2002: 6). Droughts are recurring and desertification is of serious national concern (Government of Namibia 2002: 3).

Central Northern Namibia is situated in the Cuvelai River Basin. The Cuvelai River is an endoreic river without discharge outlet to the sea, some 430 km in length, rising in south-western Angola and draining towards the Etosha Pan in northern Namibia. The Cuvelai is perennial for about 100 km before is ramifies into a delta of ephemeral water courses which crosses a broad plain of low relief, crossing the border between Angola and Namibia. Runoff in the Cuvelai is erratic and relatively low, varying between no flow and 100 million m³ /year, and being on average less than 5.0 million m³ /year as measured in Oshakati, Namibia. The ephemeral wetlands, called *oshanas*, form in shallow depressions of the Cuvelai system, originating in Angola and flowing into the Etosha Pan during years of very high rainfall (Heyns 1995: 477). The region is characterized by mostly brackish or very saline groundwater (over 5 g/l) and an absence of perennial rivers. Presently, most drinking water is abstracted from the Calueque Dam, on the Kunene River, which is shared between Angola and Namibia (Figure 15).



Cartographical basis: Michelin 955, Surveyor General (1994); Republic of Namibia 1:1,000,000, Republic of South Afica (1971); Owambo. (modified). Department of Water Affairs (1995); Water Supply Network & Boreholes Distribution; Owambo. Bittner Water Consult (BIWAC) (2004); Demarcation of Water Basins on National Level.

Steffen Niemann 2006

Figure 15: The Cuvelai-Etosha Basin and its regional context (Niemann 2006, in Liehr 2008: 432

The water is transported through open concrete and earthen canals (150 km) and pipelines (2,000 km), making it one of the largest water supply networks in Africa (Heyns 1995: 477, Liehr 2008: 445). It supplies water to numerous towns, villages and settlements, however few settlements have access to such supplies in sufficient quantity. Further important sources of water are the o*shanas* and hand-dug wells and dams which impound the erratic rainfall and runoff (Heyns 1995: 477, Government of Namibia 2002: 6, Liehr 2008: 445, Sturm et al. 2009: 777). Although the region lies in the more humid regions of Namibia, surface and groundwater resources are currently overused and conflicts over water rights occur (Kluge et al. 2008: 52).

3.1.4 Vegetation and land use

Namibia can be described as land between to deserts, the Namib and the Kalahari. Annual rainfall determines the three main vegetation zones: deserts (46%), savannas (37%) and woodlands (17%). Vegetation is distributed over 46% of the country (Government of Namibia 2002: 3). The *oshanas*, natural wetlands, have been identified as Namibia's most threatened category of ecosystem and its flow of water has been declining since the end of the 1970s (Government of Namibia 2002: 38).

Less than 2% of the land is arable, because of limited rainfall. Beef, sheep and goats production is the most common land use, although game farming and mixed wildlife and livestock production is a fast-growing industry (Government of Namibia 2002: 7). Current and past land patterns in Namibia are determined by Namibia's political history, ecology and climate. Nomadic pastoralism, dictated by the availability of grazing and water was practiced extensively during the pre-colonial period.

3.1.5 Economy and the agricultural sector

GDP grew by 4.1% on average during the period 1994 to 2000, with some fluctuations mainly due to world commodity prices and climatic conditions (Government of Namibia 2002: 15). The country is highly dependent on climate sensitive sectors, consisting of natural resource based production such as agriculture, fisheries and mining, which account for about 30% of the total GDP (Lange 2003, in Reid et al.2007a: 7).

The agricultural sector contributes 5.6% to GDP (Central Bureau of Statistics 2000, in Government of Namibia 2002: 8), which is equally shared by two sub-sectors. On one side some 4,500 commercial farmers, less than 1% of the population, employ some 35,000 laborers and occupy 52% of the agricultural land with a typical livestock farm size being 3,000ha to 20,000 ha (Werner 2000, in Government of Namibia 2002: 8). On the other side about 150.000 small-scale farmers, 70% of Namibia's population, practice subsistence crop farming and agro-pastoralism on state-owned communal land, approximately on 41% of Namibia's total land area. Less than 10% of the total land area is used for cropping and 75% for grazing. The semi-arid to arid climate does not allow much intensive agricultural production (Government of Namibia 2002: 8, 38). Agricultural output is extremely sensitive to climatic conditions and periodic droughts cause considerable stock and harvest losses. Irrigated crop production has been practiced since soon after the arrival of the first European settlers, mainly on a small scale (FAO Aquastat 2005: 8).

In the northern regions extensive cattle ranching dominates, but also dry land crop production is common. There are 274,000 ha under rain-fed cereal cropping, consisting mostly of millet, which is staple crop in communal areas, while maize is grown in commercial areas and wheat is only possible under irrigation. Over the past years activities have diversified with cotton and tobacco production and in pilot projects rice is grown in some of the *oshanas*. Dates, vegetables and other products are grown where dams supply irrigation water. Although the agricultural sector is to a certain extend adapted to prevailing climatic conditions, continued reliance on scarce water make it especially vulnerable to climate change. Rangeland is particularly threatened as human communities have become settled in areas where they previously practiced an adaptive form of extensive and nomadic pastoralism (Government of Namibia 2002: 8f). The diversification of the agricultural sector is expected to continue, with higher demand for cotton by the newly established textile industry, an expansion of tobacco plantations, and further investment in horticulture (Government of Namibia 2002: 15).

3.1.6 History and population

Namibia was colonized by Germany in the late 19th century until World War I, and then handed over to Great Britain. Being in the South African Union from 1920 on, in 1948 the National Party introduced the apartheid ideology to Namibia. Namibia reached Independence only in 1990 (Government of Namibia 2002: 16).

Namibia has a variety of ethnic groups, the Ovambo living in the north-central region being the largest with 50% of the total population. Namibia’s population is 1.8 million (latest national census 2001, National Planning Commission 2002: 3). For 2008 The World Bank estimates some 2.1 million inhabitants (The World Bank web site: Country Namibia). In 2009, 62.2% of the population lived with less than 2 US$ per day (UNDP Human Development Report 2009). The population growth rate declined from 3.1% in 1991 to 2.6% in 2001, also due to the spread of HIV/AIDS, which is prevalent among 19.3% of pregnant women. Since the mid-1990s AIDS has become the leading cause of death (Ministry of Health and Social Services 2001, in: Government of Namibia 2002: 15) and life expectancy decreased from 56 years in 1995 to 43 years in 2000 and increased to 62 years in 2010. The population is relatively young, with 42% below the age of 15 years (UNDP Namibia Country profile of human development indicators).

Namibia is an upper-middle income country with a real per capita income of about 8,300 N$ in 2001 (Government of Namibia 2002: 18) and gross national income in purchasing power parity prices of estimated 4,210 US$ in 2008 (The World Bank web site: Country Namibia). There are considerable disparities in income distribution with an estimated Gini coefficient of 0.71 (The World Bank web site: Country Namibia).

About 25% of households live in poverty (data 2000, UNDP 2001, in Government of Namibia 2002: 18).l The Human Development Index was 0.606 in 2010, placing Namibia 105th out of 182 countries (UNDP Namibia Country profile of human development indicators). The Government is the single largest employer in the country. Unemployment is at 35% (data 1997, Government of Namibia 2002: xi, 17). Considerable achievements after Independence in school enrollment and literacy have been offset by declining life expectancy due to HIV/AIDS (Government of Namibia 2002: 17)

Central Northern Namibia is the most densely populated region in Namibia, with half of the population, around 1 million people, living on approximately 15% of the country's area (Sturm 2009: 777, Kluge et al. 2008, data 2001). Urbanization is at 43% (2000, in Government of Namibia 2002: 18) and rapidly increasing. Population growth is relatively high with 1.8% (data 2001 National planning Commission: 3).

3.2 Climate change projections and impact for Northern Namibia

Climate change will exacerbate the vulnerability of national, local and household livelihoods, economies and environments and could jeopardize development including the achievement of the Millennium Development Goals (van Steenbergen and Tuinhof 2009: 4). The Intergovernmental Panel on Climate Change (IPCC) recognizes Africa to be "one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity" (IPCC 2007: 65). Few scientific studies address the impacts of global climate change specifically for Namibia and in particular the central northern region. The Fourth Assessment Report (AR4) of the IPCC from 2007 presents some information of very broad regional relevance (IPCC 2007).

3.2.1 Changes in temperatures

For the 20th century the IPCC reports a mean decadal temperature increase in Namibia of 0.2 °C per decade, which is three times the global mean temperature increase reported for that period (IPCC 2007: 46). Until 2100 all twenty-one models considered by the IPCC in the Fourth Assessment Report project under all emission scenarios an increase in mean annual temperature and in both the minimum and the maximum monthly temperatures (IPCC 2007: 46). The Working Group I of the IPCC (Christensen et al. 2007: 867) presents differences in near-surface temperature for the years 2080 to 2099 relative to the years 1980 to 1999, in the A1B projection, averaged over the South African sub region (35°S, 10°E to 12°S, 52°E). Annual temperature increase lays between 1.9°C to 4.8°C (Figure 16), roughly 1.5 times the global mean response.

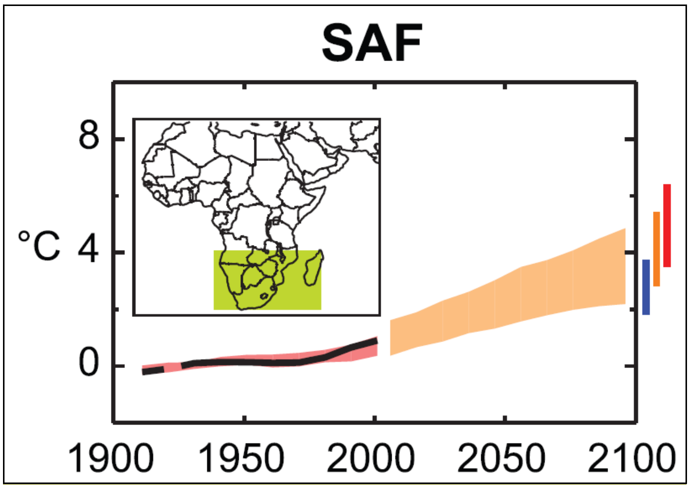


Figure 16: Temperature anomalies with respect to 1901 to 1950 for the south African sub region for 1906 to 2005 (black line) and as simulated (red envelope) by multi model data models incorporating known forcings; and as projected for 2001 to 2100 by multi model data models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are present for less than 50% of the area in the decade concerned. (Christensen et al. 2007: 868).

The projected changes in temperature and precipitation are given for the A1B of the Special Report on Emissions Scenarios (SRES) of the IPCC. The storyline for the A1 scenario family is “a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies”. The A1B scenario implies the “development of energy technologies balanced across energy sources” (IPCC 2000: 4).

For this future scenario half of the models project warming within about 0.5°C of the median values. The largest responses in Southern Africa occur in the spring period from September to November with increases of 2.1°C to 5°C (Table 1) (Christensen 2007: 854).

Table 1: Projected changes in temperature [%] for 2091 to 2100 relative to 1980 to 1999 from a set of 21 global models in the multi model data (MMD) for the A1B scenario. Values are given quarterly and as annual mean (Christensen 2007: 854).

	Minimum	Median	Maximum
DJF	1.8	3.1	4.7
MAM	1.7	3.1	4.7
JJA	1.9	3.4	4.8
SON	2.1	3.7	5.0
Annual	1.9	3.4	4.8

Table 1 displays regional averages of temperature projections from a set of 21 global models in the multi model data for the A1B[1] scenario. The mean temperature responses are first averaged for each model over all available realizations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the Table shows the minimum, maximum, median (50%) values for temperature (°C) change among the 21 models, given quarterly and as annual mean (Christensen et al. 2007: 854).

Christensen et al (2007: 868) state that to date there is insufficient evidence from regional climate models (RCMs) to modify the large-scale temperature projections from general circulation model (GCMs). However, Tadross et al. (2005, in Christensen et al. 2007: 868) project changes in the A2 scenario for southern Africa that are lower than those in the general circulation model and near the low end of the spread in the multi model data models, likely due to a weaker drying tendency than in most of the global models.

For Namibia the Japanese High Resolution general circulation model (20 km), as indicated by the World Bank, projects a mean future temperature increase for 2031 to 2050 of 2°C, which is same for all seasons while for 2100 it projects an annual increase of 3°C (World Bank climate portal).

3.2.2 Changes in precipitation

Precipitation projections are generally less consistent than temperature projections. To some of the most robust features of the precipitation response over Africa in the multi model data-A1B projections, include drying in much of southern Africa. The large-scale picture is one of drying in much of the subtropics, which is a plausible hydrological response to a warmer atmosphere, a consequence of the increase in water vapor and the resulting increase in vapor transport in the atmosphere from regions of moisture divergence to regions of moisture convergence (Christensen et al. 2007: 868). In southern Africa, such processes produce drying that is especially robust in the extreme southwest in winter, a manifestation of a much broader-scale pole ward shift in the circulation across the South Atlantic and Indian Oceans. However, the drying is subject to the caveat that strong orographic forcing may result in locally different changes. The robust drying in winter corresponds to the dry season over most of the region and does not contribute to the bulk of the annual mean drying.

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[1] SRES A1B refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. B1 refers to balanced technologies across all sources (IPCC 2007: 44).

More than half of the annual mean reduction occurs in the spring and is mirrored in some regional climate model simulations for this region. To an extent, this can be thought of as a delay in the onset of the rainy season. This spring drying suppresses evaporation, contributing to the spring maximum in the temperature response (Christensen et al. 2007: 868).

Several climate change projections based on regional climate model simulations are available for southern Africa. Tadross et al. (2005) examine two regional climate models: Providing Regional Impacts for Climate Studies (PRECIS) and Mesoscale Model version 5 (MM5) for southern Africa in a time-slice atmospheric general circulation model based in turn on lower-resolution Hadley Centre Coupled Model (HadCM3) coupled simulations for the Special Report on Emission Scenarios (SRES) A2 scenario. During the early summer season, October to December, both models predict drying over the tropical western side of the continent, responding to the increase in high-pressure systems entering from the west, with MM5 indicating that the drying extends further south and PRECIS further east. The drying in the west continues into late summer, but there are increases in total rainfall towards the east in January and February, a feature barely present in the ensemble mean of the multi model data model. Results obtained by downscaling one global model must be assessed in the context of the variety of responses in southern Africa among the multi model data models (Christensen et al. 2007: 868).

Table 2: Precipitation Response [%] for 2091 until 2100 for the A1B scenario (Christensen 2007: 854)

	Min	25	Median (50)	75	Max
DJF	-6	-3	0	5	10
MAM	-25	-8	0	4	12
JJA	-43	-27	-23	-7	-3
SON	-43	-20	-13	-8	3
Annual	-12	-9	-4	2	6

Table 2 shows the regional averages of precipitation projections from a set of 21 global models in the multi model data for the A1B scenario. The mean precipitation responses are first averaged for each model over all available realizations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median (50%) values among the 21 models, for precipitation (%) change. For June to November al models indicate a negative sign, for decreasing precipitation (colored in darker blue), so that the negative signal can be considered significant at the 95% level (Christensen et al. 2007: 854).

Projections for the 2080 to 2099 period indicate precipitation decreases of -12% to increases of +6% annually. During the dry season from June to August precipitation is projected to decrease from -43% to -3 %, with high certainties. During the rainy season from December to February precipitation is projected to decrease by -6% to increase by +10%, but tied to high uncertainties, as less than 2/3 of the models considered agree in the sign of change (IPCC 2007: 45). More than half of the models project annual temperature decreases. For June to November all models project precipitation decreases, while for December to May half of the models project decreases and half increases.

Shongwe et al. (2009: 3819) investigate likely changes in mean and extreme precipitation over southern Africa using an ensemble of twelve general circulation models prepared for the IPCC Forth Assessment Report. For the western parts of southern Africa the study found an increase in the severity of dry extremes as well as a statistically significant decrease in mean precipitation during austral summer months, December through February. In addition a notable delay in the onset of the rainy season is projected together with an early cessation in many parts of the region, leading to a statistically significant shortening of the rainy season. Particularly for northern Namibia the study mentions downward trends in intense precipitation (Shongwe et al. 2009: 3820).

Also other authors acknowledge, that precipitation is expected to decrease due to weaken of the Southern African monsoon during the 2000 to 2049 period, and by the 2080s, a drying over much of the western subtropical region due to fewer rainy days and less intense rainfall is predicted (Hudson and Jones 2002; Hulme *et al*. 2001; IPCC 2001; Ruosteenoja *et al*. 2003, in Reid et al. 2007: 9). Kigotho (2005, in Reid et al. 2007: 9) adds that climate change induced warming of the Indian Ocean is likely to lead to persistent droughts in Southern Africa in the coming years, and the monsoon winds that bring seasonal rain to sub-Saharan African could be 10 to 20% drier than 1950 to 2000 averages. Within Namibia, rainfall reductions are expected to be greatest in the northwest and central regions. Particularly strong reductions are expected in the central areas around Windhoek and surrounding highlands (Midgley et al. 2005, in Reid et al. 2007: 9). The largest projected changes in precipitation are associated with the highest projected temperature changes and projected to occur in the central, inland regions (Government of Namibia 2002: 35). In Namibia both rainfall and temperature are sensitive to the El-Nino Southern Oscillation (ENSO) effect, with periods below-average rainfall and above-average temperature during El-Nino conditions. Rainfall in the future is projected to become even more variable than at present (Government of Namibia 2002: 35).

3.2.3 Changes in evaporation

In sub-humid zones global warming is predicted to reduce soil moisture and reduce runoff. In Namibia, even if rainfall changes little from present levels, the water balance is expected to become drier due to temperature increase and consequently an increase in evaporation rates. An increase in evaporation of about 5% is expected per degree of warming (Government of Namibia 2002: 36). Together with rainfall decreases Namibia is likely to face severe water shortages. Less than 2% of the rain falling on Namibia becomes runoff and most of the discharge is in form of ephemeral pans, rivers and the *oshanas* in the north. Less than 1% of the rainfall becomes groundwater recharge. Central Northern Namibia already now experiences a net water deficit of around -2100 mm/ year, calculated by subtracting mean annual rainfall from potential evaporation. (DWA, 1991, in Government of Namibia 2002: 36)

3.2.4 Key uncertainties

Key uncertainties concern the equilibrium climate sensitivity and the expected warming for a given CO_2-eq stabilization scenario. Also uncertainty in the carbon cycle feedback creates uncertainties in the emissions trajectory required to achieve a particular stabilization level. Models differ considerably in their estimates of the strength of different feedbacks in the climate system, particularly cloud feedbacks, oceanic heat uptake and carbon cycle feedbacks. Cloud feedbacks remain the largest source of uncertainty (IPCC 2007: 38). In addition, the confidence in projections is higher for some variables (e.g. temperature) than for others (e.g. precipitation), and it is higher for larger spatial scales and longer time averaging periods (IPCC 2007: 73).

3.2.5 Impacts of climate change

The government perceives climate change as one of the most serious threats to the wellbeing of Namibia’s population (Government of Namibia 2002: 36). This was also confirmed by stakeholder interviews in the region conducted by Liehr (2008: 444). A direct effect of the predicted temperature increase is a higher evaporation rate and together with changes in rainfall pattern, water availability will be reduced. Decreases in precipitation during the growth season December through May would have the most negative impacts and limit the capacity of the environment to provide essential ecosystem services. Set against projected increases in water demand, this will adversely affect livelihoods and exacerbate prevailing water-related development constraints (Government of Namibia 2002: 36).

Particularly the country’s poor rural population, who depend on dry land cropping such as pastoralists and dry lands populations, will be affected most (Reid et al. 2007: 9, 23). In fact, the most severe economic consequences are predicted, with medium to high levels of confidence, for traditional subsistence agriculture, which relies on crop and livestock farming. Already now the sector is sustained by scarce natural resources and constrained by limited financial resources, technologies and skills. Much land used for agricultural purposes is marginal, and changes in rainfall variability as well as quantity could mean agriculture will no longer be viable in these areas (Reid et al. 2007: 15). In some regions, dry land cropping is even predicted to disappear entirely. Therefore, in a worst-case scenario, there could be a substantial decrease in production in this sector at a national level, and even in a best-case scenario, a significant decrease should be expected. Estimated reductions are in the range of 40 to 80% of production at national level (Reid et al. 2007: 23). Both subsistence cropping in the form of millet, on which most rural households in the north of Namibia depend, and commercial cropping in the form of maize, are likely to be negatively impacted by climate change (Government of Namibia 2002: 38). In the agro-silvi-pastoral zones in the north central region, it is anticipated that dry land crop production would also suffer considerable losses, but that these losses could be partially offset by greater incentives for use of perennial crops and natural resources such as trees. Increases in irrigated production of high value crops, with questioned viability, and increases in irrigated subsistence farming and local market production are predicted. Expected impacts of climate change on agricultural production in the north-central region are a decrease of livestock by -15% to -30%, halving of dry land cropping (-50%) and an increase of irrigated crops by +15% (Reid et al. 2007: 16). This will have implications for human health and increase unemployment and poverty (Government of Namibia 2002). As a consequence the process of urbanization will be intensified and new challenges will arise in terms of policies for sustainable development and their implementation, demanding adaptation measures (Boko et al., 2007, in Liehr et al. 2008: 444).

3.3 Rainwater harvesting in Namibia and project location Epyeshona village

In Namibia in situ rainwater harvesting is commonly practiced, such as collecting water in excavated holes in micro catchments or in so called *dams*. Despite its potential, ex situ rainwater harvesting is not practiced so far. Recently, few organizations became involved in rainwater harvesting for rural communities. For instance UNICEF has supported the construction of around 40 ferrocement rainwater tanks with capacities of 5 m³ at schools in the northern regions in 1992 and 1993 (Nghipandulwa, 1993; in Sturm et al. 2009: 776).

In Epyeshona village in northern Namibia, ex situ rainwater harvesting is only practiced on a small scale by few households, mostly by women, by putting available washing basins and buckets under corrugated iron roofs each time it rains. Rainwater is used for drinking, washing clothes, watering the garden, cooking and bathing. Due to the absence of larger containers and gutters to collect water at a single entry point only small amounts of rainwater are harvested which are often insufficient (CuveWaters 2007: 25, Jokisch 2010: 6).

For a pilot project of rainwater harvesting systems, the rural village of Epyeshona was chosen, located around 10 km north of Oshakati, in Okatana constituency, Oshana region (Figure 17) (Deffner et al. 2008: 7, 10).

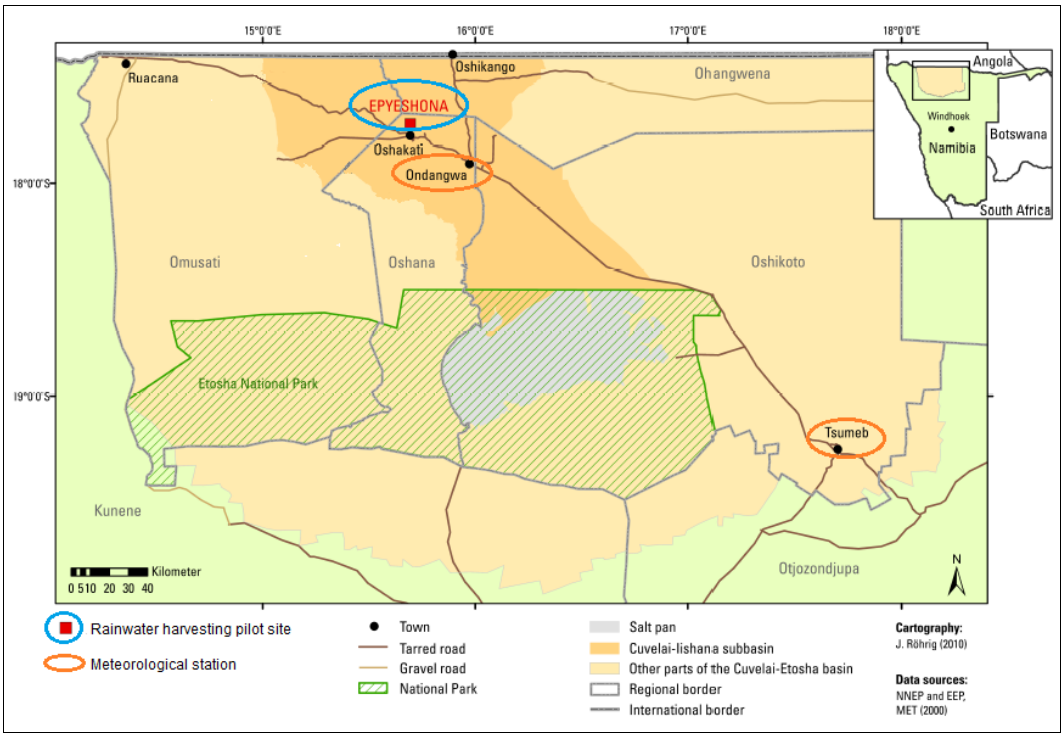


Figure 17: Location of the study area in the Cuvelai Basin in the Oshana region of Central Northern Namibia (Röhrig 2010, marked project region and meteorological station)

Epyeshona consists of around 80 households with 5 to 15 persons, which are widely spread over the area. The Namibian National Planning Commission (2006: 7) defines households as “Group of persons, related or unrelated, who live together in the same homestead/ compound, but not necessarily in the same dwelling unit. They have a common catering arrangement and are answerable to the same head.” Most of the residents are unemployed, practice subsistence farming or sell traditional drinks. About 15 households practice small-scale gardening (CuveWaters 2009). The sanitation infrastructure of the village is either rudimentary or non-existent. Since 1993, Epyeshona has been connected to the water grid with three communal water points, which are used by about 10 households (13%) (CuveWaters 2008b). The furthest distance for the residents to drinking water is 1 km. The water points are operated and managed by water point committees and only opened for some hours a day to control vandalism and violation. The amount of drinking water is restricted to 150 l/ day per household. 70 households (87%) have private taps, whose usage is limited to 10 m^3 per month. Besides grid-bound supply, other important water sources, especially for livestock, are an excavated dam and the temporal oshanas during the rainy season. The domestic water consumption has been specified by the residents with 591 l per day and household or, assuming 15 persons per household, 39 l per day and person (CuveWaters 2008b).

In 2009 three households were chosen by the community for the construction of pilot harvesting facilities with each 30 m^3 tanks for roof collection. Three tank options are being tested; brick, ferrocement and plastic tanks. One tank is connected to a roof with 87 m^3 surface and is estimated to harvest 35 m^3 annually, while the other two are connected to a roof surface of 100 m^2 and could harvest 40 m^3 annually. In addition the community determined the place to construct an underground catchment with 120 m^3 tank volume and 480 m^2 catchment size, harvesting annually 170 m^3, for usage of five to six households[2] (Jokisch 2010: 7). Estimated annually harvested rain is calculated by multiplying average annual precipitation with the surface area of catchment and a specific runoff coefficient.

As the harvested rainwater is intended to be used mainly for watering gardens, also a small greenhouse, a drip irrigation plant with pipes and pumps were built. One garden of 150 m^2 is planned next to each household water tank while six household gardens of each 150 m^2 are planned next to the underground tank. Tomatoes and cabbages were planted (Jokisch 2010: 24, 33, 34) after the construction at the beginning of 2010. For the following study, only the rooftop rainwater harvesting facility with a catchment size of 100 m^2 is going to be analyzed.

3.4 Urban Gardening

“Urban and peri-urban agriculture is the practices of producing vegetables and fruits within urban environments for household consumption as well as for sale to the rapidly growing urban population.” (Dima et al. 2002: 7). Dima et al. (2002) analyzed the status of urban agriculture in Oshakati, suited 30 km south of Epyeshona, gathering extend of cultivation, economic, socio-cultural and technical aspects as well as constrains and reasons for gardening. Nantanga et al. (2007: 3) analyzed existing small-scale irrigation projects in northern Namibia and suggest that average water demand in small scale horticulture and small-scale irrigation is 1.2 to 1.5 m^3 per m^2 and year. Soils in the project area are sandy but nevertheless highly suitable for crop cultivation (Figure 18).

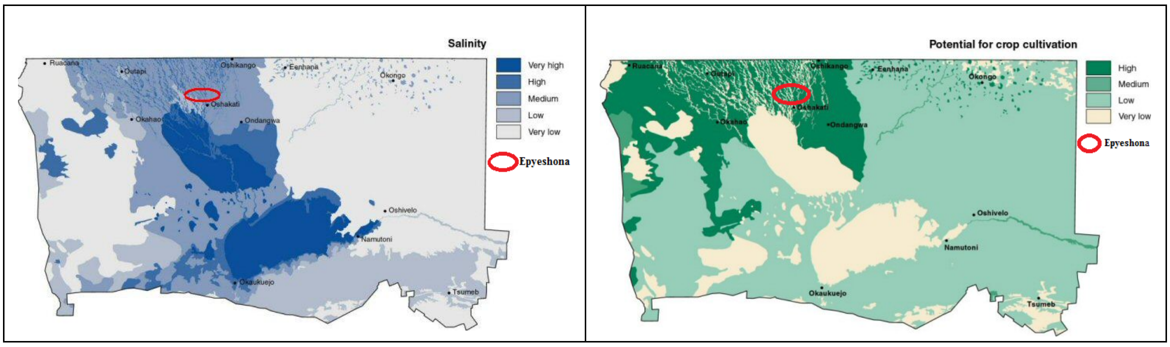


Figure 18: Potential for crop cultivation and salinity in north central Namibia (MET website)

Calculation:

mean annual rainfall (0.472 m) * runoff coefficient for ground catchment (0.75) * catchment size (480 m^2) = 169.9 m^3

mean annual rainfall (0.472 m) * runoff coefficient for roof catchment (0.85) * catchment size (100 m^2 or 87m^2) = 40 m^3 or 35 m^2

Gardening would bring numerous advantages for village inhabitants such as increased food security, a healthier diet and further income generation through marketing (CuveWaters 2009: 17). Gardening products are estimated to have a high potential, especially in informal markets, as there is a high demand for traditional food stuffs including vegetables. This would also reduce the dependence on imported vegetables and fruits from South Africa (Dima et al. 2002: 74).

A study issued by the FAO from 2002 (Dima et al. 2002) found that urban agriculture is practiced by 72% of the residents of Oshakati, especially by women (58%). Over 23 types of vegetables and fruit trees are grown on tiny plots, but most common crops grown are maize (88%), tomatoes (41%), pumpkins (26%), water melons (24%), sweet potatoes (23%) and red peppers (17%). Most of the produce is consumed by the household or given to friends and contributes to improvement of their nutritional status. Only some 25% of the farmers reported some selling to augment household income (Dima et al. 2002: 11, 12, 15). Most of the respondents would like to grow tomatoes, maize, cabbage, fruit trees, onions, beans, sweet potato, chilies, water melon and carrots (Dima et al. 2002: 60). Nantanga et al. (2007:3) suggest that main crops planted in the region are staple pearl millet, sorghum, cowpeas and melons, which are only planted during the rainy season. Numerous small scale irrigation projects for substance purposes produce mainly vegetables including onions, green peppers, spinach, cabbages and tomatoes.

In the city of Oshakati plots are acquired from the headmen (51%) and from the municipality (47%). This concurrent allocation by headmen, who claim traditional authority to the land without being recognized by government authorities, is a major bottleneck to effective planning. Many inhabitants, especially women, are very interested in gardening and 67% wish to extend their garden activities (Dima et al. 2002: 55, CuveWaters 2009: 17). Similarly those with no gardens have expressed interest to start vegetable gardens, if they are provided with space and initial capital. (Dima et al. 2002: 50). 72% of the respondents produce vegetables only during the summer as to benefit from the summer rains. Reliance on rainwater is limited since amount, duration and starting of rain is unpredictable (Dima et al. 2002: 75), while other sources of water are limited as well or too expensive.

In fact, the biggest problem and limiting factor is the lack of sufficient and cheap water (51%). 83% of respondents in Oshakati state that they need help to collect rain (Dima et al. 2002: 40). Other constrains of urban agriculture are pest attacks (38%) and theft of produce (24%). Reasons for not having a garden are mostly the lack of space (34%) (Dima et al. 2002: 40). Another important problem is the lack of information regarding the types of crops to grow, the chemicals to use and the prices, producers would receive for their products. This is in part due to the absence of extension services to the producers and the lack of policy on urban agriculture (Dima et al. 2002: 12). Existing marketing outlets are limited to the locality and hence not reliable. Dima et al. (2002: 15) recommend that the small growers should be assisted to organize themselves into producer cooperative so that they can break into the main market. In addition, the government should introduce policies to encourage the production of high value crops for the market, allocate responsibilities among concerned authorities, provide guidelines of correct husbandry and protection of the environment as well as inject micro loans to enable producers to purchase inputs including appropriate technology.

In Epyeshona only few households have small gardens to grow vegetables, which are mainly rain fed, due to water shortages and payment difficulties in the village, however ,also tap water or used water is used. A garden usually has one to two fruits trees, such as papaya, mango, guava, sea lemon, while grown vegetables are mostly spinach. The major growth period is in spring (September through November) (CuveWaters 2010: 2) or as Dima et al. (2002: 15) suggest, vegetable production takes place during the summer rains. Garden produce is mainly used for household consumption and not for sale. During project workshops inhabitants liked the idea of rainwater harvesting in order to be able to have own gardens and to improve diet and income possibilities (CuveWaters 2010: 2, CuveWaters 2007a: 10).

4 Methods, procedure and data

4.1 Methods

4.1.1 The tank model

4.1.1.1 Statistical probability analysis of precipitation

Planning and management of harvesting rainwater in semi-arid zones presents difficulties due to the inherent degree of precipitation variability (Critchley et al. 1991:3.3). Crop water requirements can be partially or fully covered by rainfall. However, as rainfall varies considerably from year to year, the use of mean values of rainfall should be avoided if more than 10 years of annual rainfall data are available, such as for this study (Savva and Frencken 2002: 58).

The so called dependable rainfall, which is also called design rainfall, is the rain that can be accounted for with a certain statistical probability of occurrence or exceedance, determined from a range of historical rainfall records. For instance, the dependable rainfall with a 75% probability of exceedance means that on average this amount of rainfall will be reached or exceeded in 3 out of 4 years and therefore the crop water requirement will also be met in 3 out of 4 years A higher level of dependable rainfall (80% or 90% probability of exceedance) may need to be selected during the period when crops are more sensitive to water stress and where yields would be severely affected by water stress (Critchley et al. 1991: 3.3, Savva and Frenken 2002a: 59). This study chooses to use the 75% dependable rainfall, as it considers it to represent an appropriate level of uncertainty without diminishing rainfall excessively. With this method, the probability of underestimating irrigation water requirments is lowered considerably. However, in 2.5 out of 10 years irrigation requirements will be higher due to less rainfall.

A graphical method to determine the frequency of occurrence of yearly rainfall is described in the FAO manual by Critchley et al. (1991). First annual rainfall totals for the cropping season are ranked according to their value. Then, the probability of occurrence P (%) for each of the ranked observation can be calculated from Equation 1, recommended for N=10 to 100 (Reining et al. 1989, in Critchley et al. 1991: 3.4).

Equation 1: Probability of occurrence for ranked observation (Reining et al. 1989, in Critchley et al. 1991: 3.4).

$$\boxed{P(\%) = \frac{m - 0.375}{N + 0.25} \bullet 100}$$

Where:
P= probability [%] of the observation of the rank m
m= rank of the observation
N= total number of observations used

Ranked observations are plotted against the corresponding probabilities and fit to a curve. From this curve the probability of occurrence or exceedance of a rainfall value of a specific magnitude can be obtained (Critchley et al. 1991: 3.4).

The analysis of the precipitation pattern was done using the statistic software R 2.11.0, illustrating the data in a boxplot (Figure 19). A boxplot graphically illustrates groups of numerical data through a five-number summary: the smallest observation (sample minimum), first quartile (0.25 quantile), median (0.5 quantile), third quartile (0.75 quantile), and largest observation (sample maximum). Observations considered to be outlier are indicated with circles. The median divides the lower half of the sample and the upper half in the middle, half of the sample values being smaller, half being higher. The first quartile cuts off lowest 25% of data, the third quartile cuts off highest 25% of data, or lowest 75% (Schneider 2006: 2).

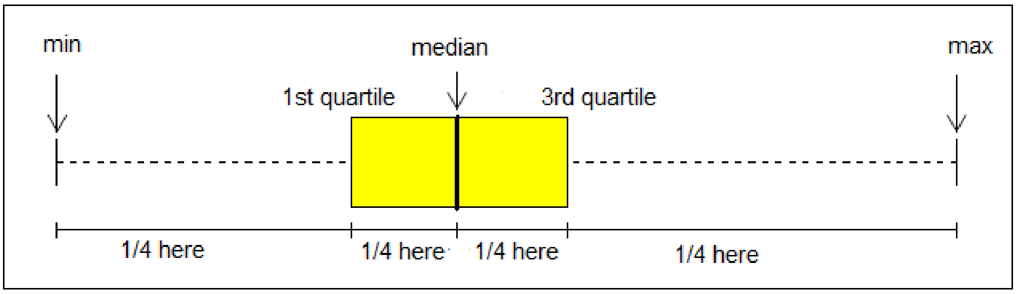


Figure 19: Boxplot (Schneider 2006: 3)

Additional statistical analysis of annual and monthly precipitation is done with Excel. Determined were monthly and annual mean precipitation, standard deviation, minimal precipitation recorded and maximal precipitation recorded, the range, as well as the probability of exceedance of precipitation at level 90%, 75% (0.25 quantil), 50% (0.5 quantil), 25% (0.75 quantil) and 10% as well as a trend line of mean precipitation.

With the statistic program R 2.11.0 a linear regression t-test has been carried out in order to determine whether the slope of the regression line of the mean precipitation from 1902 to 2009 differs significantly from zero. The null hypothesis implies that the slope of the regression does not differ significantly from zero, and there has been no change in precipitation since 1902. For the significance of the result, different levels of confidence can be applied, such as 5%, or 1%. If the significance level reaches 5% (p-value < 0.05) or better 1% (p-value < 0.01) the null hypothesis can be rejected. The p-value is the probability of observing a sample statistic as extreme as the test statistic. If the p-value is less than the significance level (p>0.05, p>0.01), the null hypothesis can be rejected, with a significance level of 5% or 1%. The significance level means that the null hypothesis could be exact in 1% of cases, and the slope of the regression differs significantly from zero only by chance.

4.1.1.2 Climate change

For the estimation of water demands for gardening using harvested rainwater, the climate situation at the beginning (2010) and at the end (2050) of the life cycle of the rainwater harvesting facility will be examined. Future projected temperature and precipitation changes are going to be considered as well as crop evapotranspiration changes. The IPCC is the reference institution in the field of climate change that resembles and presents results of numerous climate models. As previously described in chapter 4.1.1.2 “Climate change”, the Fourth Assessment Report of the IPCC presents data for climate change in the South African subcontinent until 2080 to 2099 (Christensen et al. 2007). In order to estimate a corridor for climate change data in the region until the end of the rainwater harvesting facility life cycle in 2050, available data projected for 2031-2050 from the Japanese High Resolution general circulation model were looked at and compared to their data for 2091 to 2100. It was found that temperature data for 2031 to 2050 differ from the data for 2091 to 2100 with the ratio 2:3, being lower by 1/3. Therefore, the data corridor of 21 models provided by the IPCC was also reduced by 1/3, regarding temperature and precipitation response, considering that the IPCC states that the signal is assumed to increase linearly in time (Christensen et al.: 854). Crop evapotranspiration changes are going to be computed with Cropwat, the software designed and recommended by the FAO. For the calculation of crop evapotranspiration, future changes in relative humidity and wind speed due to climate change are not going to be considered, as well as changes in the frequency of extreme events. The reason for this is that model projections for future changes in humidity and wind speed are highly uncertain and information for the project area is not available.

4.1.1.3 Estimating crop water requirement and irrigation requirement

The FAO (1984 in Savva and Frenken 2002a: 4) defines crop water requirement (CWR) as “water needed to meet the water loss through evapotranspiration of a crop, being disease-free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment” or shorter “the water used by crops for cell construction and transpiration” (Savva and Frenken 2002a: 54). Irrigation requirement (IR) refers to “the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements” (Savva and Frenken 2002a: 4). If irrigation is the only water supply to the plant, the irrigation requirement is equal or greater than the crop water requirement to allow inefficiencies in the irrigation system, while if the crop receives water from other sources such as rain, the irrigation requirement will be less than the crop water requirement (Savva and Frenken 2002a: 54).

The procedure recommended by the FAO for the estimation of crop water requirements and irrigation requirement is the crop coefficient method introduced by Doorenbros and Pruitt (1984), updated by Allen et al. (1998), and explained in detail by Savva and Frenken (2002a). The procedure is summarized in Figure 20. The containing parameters are explained in the following section.

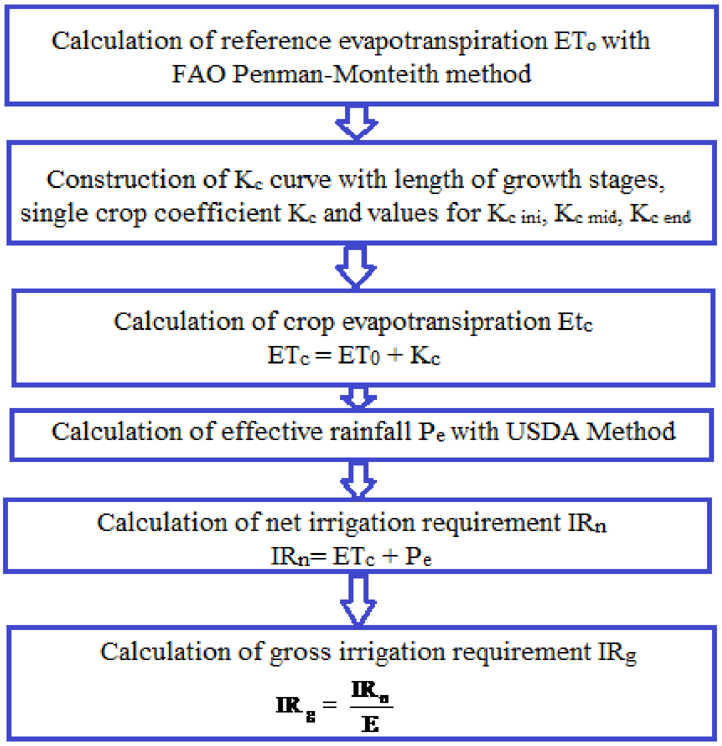


Figure 20: Procedure for calculating crop evapotranspiration ET$_c$ under standard conditions and irrigation requirement (own arrangement according to Allen et al. 1998, Savva and Frenken 2002a: 36 f)

Reference evapotranspiration (ET$_o$)

For the reference evapotranspiration ET$_o$, the evapotranspiration from a reference surface, an hypothetical grass reference with specific characteristics not short of water, is used. As a result ET$_o$ is a climatic parameter that expresses the evaporative demand of the atmosphere at a specific location and time of year. It can be computed from weather data without considering crop and soil factors. The calculation procedures for estimating ET$_o$ is given in Equation 2 (Savva and Frenken 2002a: 2,35).

Equation 2: Calculation of the reference evapotranspiration according to the Penman-Monteith Method (Allen et al. 1998: chapter 2, Savva and Frenken 2002a: 9)

$$\boxed{ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}}$$

Where:
ET$_0$= Reference evapotranspiration [mm/day]
R$_n$= net radiation at the crop surface [MJ/ m² per day]
G= Soil heat flux density [MJ/ m² per day]
T= Mean daily air temperature at 2 m height [°C] =(Tmax + Tmin)/ 2)
u$_2$= Wind speed at 2 m height (m/sec)
e$_s$= Saturation vapor pressure [kPa]
e$_s$ – e$_a$= Saturation vapor pressure deficit [kPa]
Δ= Slope of saturation vapor pressure curve at temperature T [kPa/ °C]
Γ= Psychometric constant [kPa/ °C]

The equation requires input of climatological records of minimal and maximal air temperature, mean relative air humidity ((RH_{max} + RH_{min})/2), wind speed and hours of daily sunshine. Site location, altitude above sea level [m] and latitude (degrees north or south) are needed, in order to adjust some parameters such as the local average value of atmospheric pressure and to compute extraterrestrial radiation as well as daylight hours (Savva and Frencken 2002: 9).

Crop evapotranspiration (ET_c)

Crop evapotranspiration (ET_c) is the crop water requirement (CWR) for a specific cropping pattern during a certain time period (Savva and Frenken 2002a: 59). Crop evapotranspiration can be calculated under standard conditions (ET_c) or under nonstandard conditions ($ET_{c\ adj}$). Standard conditions refer to crops grown in large fields under non-limiting agronomic and soil water conditions. With non-standard conditions such as low soil fertility, salt toxicity, waterlogging, pests, diseases and the presence of a hard or impenetrable soil horizon in the root zone, stress coefficients are introduced (Savva and Frenken 2002a: 35). When water supply does not meet crop water requirements, water stress develops in the plant which adversely affects crops growth, crop yield and the quality of the produce. The extent of adverse effects depends on the crop species and variety on one hand and the time of occurrence of water deficit on the other. In general, crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early and vegetative and after establishment and late growth stages, i.e. ripening (Savva and Frenken 2002a: 92). In this study for reasons of simplicity and lack of exact data the crop evapotranspiration ET_c will be calculated under standard conditions, by multiplying ET_o with a crop coefficient K_c as given in Equation 3. This is also illustrated in Figure 21.

Equation 3: Calculation of crop evapotranspiration [mm/day] (Savva and Frenken 2002a: 35)

$$\boxed{ET_c = ET_0 \bullet K_c}$$

Where:
ET_c= Crop evapotranspiration [mm/day]
ET_o = Reference crop evapotranspiration (mm/day)
K_c = Crop coefficient

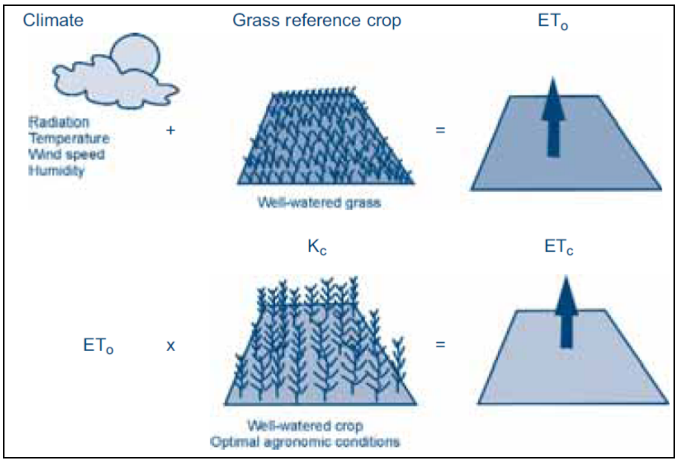


Figure 21: Calculation of reference crop evapotranspiration and crop evapotranspiration (Allen et al. 1998, in Savva and Frenken 2002a: 3)

Crop coefficient K_c

There are two approaches for calculating crop evapotranspiration; the single and the dual crop coefficient approach. The crop coefficient K_c is basically the ratio of ET_c to ET_o and expresses the difference in evapotranspiration between the cropped area and the reference grass surface. In the dual crop coefficient approach, the effects of crop transpiration and soil evaporation are determined separately using two coefficients, while the single crop coefficient approach combines them into a single coefficient K_c. As the single K_c averages soil evaporation and crop transpiration, the approach is used to calculate ET_c for weekly or longer time periods and for planning purposes and irrigation system design where averaged effects of soil wetting are acceptable and relevant. In this study, the single crop coefficient will be used, due to the longer time period needed (Savva and Frenken 2002a: 35). Factors determining the crop coefficient K_c include crop type, changing crop characteristics over the growing season and, to a limited extent, the prevailing weather conditions. As evaporation is part of crop evapotranspiration, conditions affecting soil evaporation will also affect K_c. The large variation in K_c values between major groups of crops is due to the different resistance to transpiration of crops, differences in crop height, crop roughness, reflection and groundcover. K_c values for many crops increase with increase in wind speed and decrease in relative humidity, such as in more arid climates (Savva and Frenken 2002a: 36). The K_c for a given crop changes over the growing period as groundcover, crop height and leaf area changes. Four growth stages are recognized; the initial, the crop development, the mid-season and the late season stage (Savva and Frenken 2002a: 37). Based on the length of crop growth stages and the corresponding crop coefficients, a crop coefficient curve can be constructed which represents the changes in crop coefficient over the growth period, as shown in Figure 22. From the curve the crop evapotranspiration for any period within the growing season can be derived.

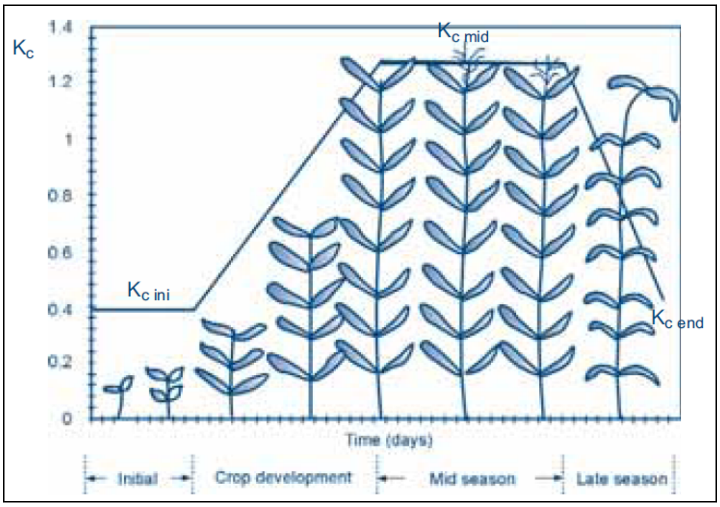


Figure 22: Generalized crop coefficient curve for the single crop coefficient approach (Allen et al. 1998, in Savva and Frenken 2002a: 39)

Factors influencing crop water requirements (ET_c)

Savva and Frenken (2002a: 40) highlight the indicative character of the data and the importance of verification and supplement with local information. The main factors affecting ET_c are climatic and soil water related factors, irrigation methods and cultural practices. If plants are sufficiently anchored and there are proper growing conditions, such as available water, nutrients and soil aeration, the ET_c is not affected, even when rooting depth is severely restricted. Available soil water effects evapotranspiration depending on crop, soil type and water-holding characteristics, crop rooting characteristics and the meteorological factors determining the level of transpiration. Shallow groundwater tables affect crop growth and therefore also the ET_c. Soil salinity reduces the crop’s ability to uptake water from the soil due to the higher osmotic potential of saline soil water. Timing and duration of water stress influences crop yield, as different crops have different critical periods for soil water stress. A properly designed, constructed and operated irrigation system will not have any effect on ET_c, with the exception of localized irrigation. The differences in the amount of water used for irrigation are due to the corresponding efficiency of the method. Localized irrigation (drip, spray jet, etc.) only wets part of the soil and lowers evaporation from the soil, therefore the overall ET_c is expected to be less. Cultural practices including the use of fertilizers, the plant population, tillage, mulching, crop residues, windbreaks or anti-transpirants may effect ET_c (Savva and Frenken 2002a: 54).

When calculating ET_c, the distance between the project area and the meteorological station can have some influence on the project crop water requirements. Changes in microclimatic environment because of the project should also be considered. With varying weather also ET_c values vary, e.g. monthly values can vary by 50% or more from one year to the other. For the planning and designing of irrigation projects, variations with time become very important. When sufficient climatic data is available (>10 years), ET_c can be calculated for each year and a probability analysis can be done. The value of ET_c then selected for design is commonly based on a probability of 75% to 80%, which could be similar to the probability in water availability. In most cases, such as for this study, sufficient data is not available to allow a probability analysis to be carried out (Savva and Frenken 2002a: 54f).

Net irrigation requirement (IR_n)

Net Irrigation Requirement (IR_n) does not include losses occurring in the process of applying the water and is derived from the field balance Equation 4:

Equation 4: Net Irrigation Requirement (IR_n) (Savva and Frenken 2002a: 57)

$$\boxed{IR_n = ET_c - (P_e + G_e + W_b) + LR_{mm}}$$

Where:
IR_n = Net irrigation requirement (mm)
ET_c = Crop evapotranspiration (mm)
P_e = Effective dependable rainfall (mm)
G_e = Groundwater contribution from water table (mm)
W_b = Water stored in the soil at the beginning of each period (mm)
LR_{mm} = Leaching requirement (mm)

The parameters for the field balance equation are going to be briefly explained in the following section. For more detailed information see Savva and Frenken (2002a).

Effective dependable rainfall (P_e)

Only the part of the rainfall is effective, which can be effectively used by the crop, depending on its root zone depth and the soil storage capacity. The rest may be lost through surface runoff, deep percolation or evaporation. Different methods exist to estimate the effective rainfall which is not going to be explained in detail. According to the FAO (Savva and Frenken 2002a: 59) one of the most commonly used methods is the one from the United States Department of Agriculture, the USDA Soil Conservation Service Method, which relates mean monthly rainfall to average monthly ETc. Calculation is shown in Equation 5.

Equation 5: Calculation of the effective rainfall with the UDSA soil conservation method (Savva and Frencken 2007:70)

$$\boxed{P_e = \frac{P_{mon}\,(125 - 0.2 \bullet P_{mon})}{125} \qquad \text{for } P_{mon} \leq 250\,\text{mm/ month}}$$

$$\boxed{P_e = 125 + 0{,}1 \bullet P_{mon} \qquad \text{for } P_{mon} > 250\,\text{mm/month}}$$

At the time of irrigation, the net depth of irrigation water that can be stored effectively over the root zone is assumed to be 75 mm, with the possibility of adaptation to local conditions through a correction factor. This study does not use a correction factor due to the lack of relevant information. In cases of low infiltration and high rainfall intensities, considerable water may be lost by runoff, which is not accounted for in this method (Savva and Frenken 2002a: 59).

Groundwater Table (G_e), water stored in the soil (W_b), leaching requirements (LR)

The contribution of the groundwater table (G_e) to the ET_c varies with depth of the water Table below the root zone, soil type and water content in the root zone. As very detailed experiments are required to determine the groundwater contribution under field conditions and since under most smallholder conditions high water tables are rare, groundwater contribution to crop water requirements is normally ignored (Savva and Frenken 2002a: 60). Water stored in the soil (W_b) from previous irrigation that can be used for the next crop, can be deducted when determining the seasonal irrigation requirements. However the effectiveness of the water stored in the root zone ranges from 40% to 90% due to losses through evaporation and deep percolation. Since most smallholder irrigation schemes in Southern Africa are located in dry areas with very low rainfall for planning purposes the contribution of water stored in the soil is considered to be negligible in such schemes (Savva and Frenken 2002a: 61). Leaching requirement (*LR*), the application of an excess amount of water during irrigation, can control a high salt content in the root zone. As a rule, when estimating irrigation requirements the leaching requirement is ignored. In addition, due to irrigation system inefficiencies, water losses due to deep percolation normally satisfy the leaching requirements (Savva and Frenken 2002a: 61). Therefore, when calculating net irrigation requirement, the parameters groundwater table, water stored in the soil and leaching requirement are going to be neglected in this study.

Gross irrigation requirements (IR_g)

Net irrigation requirement (IR_n) plus water losses incurred during conveyance and application in the field constitute the gross irrigation requirement (IR_g). Gross irrigation requirement is expressed as the ratio of net irrigation requirements to irrigation efficiency (Equation 6).

Equation 6: Calculation of gross irrigation requirement (Savva and Frenken 2002a: 65)

$$\boxed{IR_g = \frac{IR_n}{E}}$$

Where:
IRg = Gross irrigation requirements (mm)
IRn = Net irrigation requirements (mm)
E = Overall project efficiency

Efficiencies of different irrigation systems are: surface 45%, sprinkler 75% and localized 90% (Savva and Frenken 2002a: 65).

Estimating crop water and irrigation requirement using CROPWAT 8.0

In order to speed up calculations and avoid the fairly high risk of making arithmetical errors through the manual calculation, the FAO computer software CROPWAT 8.0 has been used for estimating ET_o, crop water requirements and irrigation requirements, as recommended by Savva and Frenken (2002a: 21). Cropwat calculates crop water and irrigation requirements from climatic and crop data. The Cropwat model is based on a water balance model where the soil moisture status is determined on a daily basis from calculated evapotranspiration and inputs of rainfall and irrigation. Methodologies for crop water requirements and yield response to water are used, while the actual evapotranspiration is determined from the soil moisture status. The program uses monthly climatic data (temperature, relative humidity, wind speed, sunshine hours, rainfall) for the calculation of reference evapotranspiration. It has also four different methods to calculate effective rainfall, for this study the recommended USDA S. C. method was chosen. Through the input of crop data (growth stages, K_c factors, root zone depth and allowable soil moisture depletion factor), the program calculates the crop water requirements on a decade (10-day) basis (Savva and Frenken 2002a: 67). Other crop parameters to be entered in Cropwat, with data available in Savva and Frenken (2002a), are: Crop coefficient (K_c), yield response factor (K_y) to water stress, crop height, critical depletion fraction (p) representing the critical soil moisture level where first drought stress occurs affecting crop evapotranspiration and crop production, planting and harvesting date, growth stages and rooting depth. In order to prepare field irrigation schedule three parameters have to be considered: The daily crop water requirements, the soil, particularly its total available moisture or water-holding capacity and the effective root zone depth (Savva and Frenken 2002a: 4).

Irrigation requirements throughout the year are compared with water availability to ensure adequate water support for the cropping proposals. It may be necessary to adjust the cropping pattern so as to match water availability or to reduce the area proposed to be under irrigation. It is important to realize that the calculation of crop water and irrigation requirements is a theoretical exercise, based on statistical analysis of climatic parameters, while in reality the climate is highly variable. Consequently the calculation of irrigation water requirements at planning level can only be an approximation and it is not appropriate or recommended to attempt detailed accuracy (Savva and Frenken 2002a: 78).

Planting date

The planting date is normally determined from climatic conditions, for instance, at the beginning of the rainy season in tropical climates or the beginning of spring when temperature reaches a minimum for plant growth in temperate climates. It also varies according to local agricultural practices. It is possible, for the same crop and the same climatological conditions, to choose different planting dates. This is useful for the study of different cropping patterns and the calculation of water supply schedules.

4.1.2 Cost-benefit analysis

In order to evaluate gardening activities using rainwater harvesting in economic terms, costs and benefits arising from the activity have to be identifies and weight against each other. In addition, in project analysis costs and benefits are compared to the situation as it would be without the activity. This is different from comparing the ‘before’ and ‘after’ project situation (Senkondo et al. 2004: 69f). This study, however, does not aim to evaluate the “with” or “without” rainwater harvesting situation, as it assumes that without the facility small scale gardening activities could not take place at all (see Dima 2002, Deffner 2008) and no benefits or costs would occur. This study rather aims at evaluating different cropping scenarios to use in combination with rooftop rainwater harvesting and to assess them for sustainability.

Appraisals can be basically distinguished in static and dynamic appraisal methods (Sturm et al 2009: 778). In dynamic methods, all costs and benefits of each period are reduced to a present worth (net present value) by the application of an appropriate discount rate (Gilpin 2000: 198, Sturm et al. 2009: 778). Available methods to measure economic profitability are cost-effectiveness analysis, multi-criteria-analysis, internal rate of return, equivalent annuity method or cost-benefit analysis (Gilpin 2000: 170 f, Feibel, 2003; Thommen, 2004; LAWA, 2005, in Sturm et al. 2009: 778,). Cost-effectiveness analysis is concerned with the least-cost approach to the objective. It involves an examination of the costs of alternative ways to meet objectives with a view of achieving the maximum value for the investment (Gilpin 2000: 170 f). This method is not practicable for this study, as the investment decision has already been taken and the approach requires rather complex assumptions for objectives. Multi-criteria analysis will not be used for this study, since the idea of the approach is covered by the sustainability approach of this study. Internal rate of return is also not suitable for this study, since it is mainly used in business management and compares alternative investment options and thus neglects every effect beyond the single firm or actor.

From these methods, the cost-benefit method in combination with the discounted cash flow method or the net present value (NPV) method, is applied (Feibel 2003, Thommen 2004; LAWA 2005 in Sturm et al. 2009: 778), since it is widely used throughout economics. Moreover, net present value is the standard method for using discounted monetary values to appraise long-term projects. The technique of cost-benefit analysis has a long and rewarding history. It is a methodical approach involving the measurement of costs and benefits occurring over the economic life of a project (Gilpin 2000: 198). Key steps in the dynamic net present value method are first to identify costs and benefits of a project. Secondly, costs and benefits need to be quantified in monetary terms, as far as possible. Inflows are equal to the benefits and outflows are equal to costs. Thirdly, costs and benefits are discounted over the lifetime of the project by a selected discount rate of interest and net present value is calculated (Gilpin 2000: 198, Mensch 2002: 75), as given in Equation 7.

Equation 7: Net Present Value (Mensch 2002: 75)

$$\boxed{NPV = -I_0 + \sum_{t=1}^{T} R_t \bullet (1+i)^{-t}}$$

Where:
NPV= Net present value
I= Investment
t= Time period from 0 to T
Rt= inflow-outflow in period t
T= Time horizon (life span)
i= discount factor

The results of net present value may be positive or negative. In purely economic terms, the production of a good is economically justified when the total benefits exceed the total costs (Gilpin 2000: 174-180). Considerations to be made explicit include the time horizon, the discount rate and prices and valuation of labor (Senkondo et al. 2004: 69f).

In economics, money has a time value and a given amount of money will be worth less in the future than it is today. Thus, discounting is a technique to express the relation between present and future cash flows. Profitability of alternative projects can be compared by measuring the rating of an investment in terms of its present net value. It determines the net present value of a sum to be received or paid at some future date, with a certain compound interest rate, equal the sum received or paid in the future (Wong et al 2007: 1069, Gilpin 2000: 180). The economic and social concept of discounting is highly controversial, particularly in situations in which the long-term effects on the environment are uncertain and irreversible. The choice of an appropriate discount rate is as well highly controversial (Gilpin 2000: 181). In addition, the valuation of assets outside the market economy present problems in this technique and a variety of techniques have emerged to assess values, some controversial in themselves (Gilpin 2000: 198).

For this study a mean discount rate of 5% was chosen. A problem with discounting is that late revenues are valued less, and costs in early periods valued high, leading to distortions. However, this is necessary in order to consider factors such as inflation, credit costs or alternative lost investment interests, even if in this case it could be argued, that the money would be probably spent and not invested. Therefore another approach, the static payback time method is also used (Gilpin 2000: 198).

Payback period (PB)

The static payback period or pay-off method does not take into account the time value of money, meaning that interest rates of employed capital are not considered. The payback period calculates the exact time needed to recover the investment and annual costs (Mensch 2002: 138, Wong et al 2007: 1069, Zhani and Ben Bacha 2010: 2616), as given in Equation 8.

Equation 8: Calculation of the payback period (Mensch 2002: 139, Zhani and Ben Bacha 2010: 2616)

$$\boxed{\text{Payback period} = \frac{\text{Investment and maintainance costs}}{\text{Annual cash inflow}}}$$

In summary, this study will evaluate economic profitability of the facility with the dynamic net present value method and the static payback period method. Results will be helpful in assessing profitability considering and not considering the time value of money. All currency exchange calculations in this study were done using the currency exchange website http://www.oanda.com in.

4.1.3 Sustainability Assessment

According to Pachpute et al. (2009: 2817) sustainability of rainwater harvesting systems means that “the existent harvesting, use and consumption of natural water resources through rainwater harvesting can be continued in to the future for optimal livelihood generation”. Ngigi et al. (2008) suggest that the sustainability of rainwater harvesting systems is based on three important attributes: Firstly, reliable water supply and production potential, which depend on rainfall variability, type and location of rainwater harvesting system. Secondly, the effectiveness of water use, increasing with precise water use, which is a function of local skills and investment capacities. Thirdly, minimal negative impacts on natural resources, depending of the intensity of water use, type and location of the rainwater harvesting system in reference to hydrologic sensitivity of the area (Ngigi et al. 2008). In addition, an important factor for sustainability is the certainty of income generation through sustainable rainwater harvesting systems that increase opportunities for crop intensification and investments in smallholder farming. Factors influencing the sustainability of rainwater harvesting systems are rainfall variability, runoff quality and quantity. Social and economic factors include local skills and investment capacity, labor availability and institutional support (Pachpute et al 2009: 2815). Nonetheless, Pachpute et al. (2009) acknowledge that little is known about the key factors that determine sustainability of rainwater harvesting.

In order to assess sustainability, as presented earlier in chapter 2.2.2, a large number of concepts of sustainability and approaches for assessment have been developed. Even though a large number of methodological approaches and indicators have been proposed to assess sustainability, there is no widely accepted theoretical basis for the creation of a scientifically substantiated system of indicators and especially for analysis, scale and final goal (OECD 2001, Dantsis et al. 2010: 256).

Sustainability can be analyzed on diverse spatial scales, from the field to a regional, national or even an international scale (OECD 2001, in , Dantsis et al. 2010: 256). This study aims to analyze the household scale concerning the economic dimension, household and community scale concerning social dimension and household to basin scale regarding the ecologic dimension. As a consequence also the selected indicators should be adequate for the corresponding scale.

Presently, there is a broad debate concerning the concept of strong and weak sustainability (Pearce et al. 1996: 85, Ayres 1998: 1, Neumayer 2003: 21, Waheed et al. 2009: 443). This study chooses to use the concept of strong sustainability, the non-substitutability paradigm, as it believes that natural capital cannot be duplicated by man-made one. To be truly sustainable, all three pillars are equally important and require a positive outcome, while a negative outcome in one pillar will mean that the whole project is not sustainable. Regarding the approach to Sustainability Assessment, Gibson (2000) and Pope et al. (2004) argue that the top-down or principles-based approach outweighs the bottom-up or triple bottom line approach. However, Waheed et al. (2009) suggest that literature review shows that extensive research has been done using both approaches (Waheed et al. 2009: 444). This study attempts a principle based “top down” approach as it is suggested to have numerous advantages as presented in chapter 2.2.2. Interrelations between the three pillars will be kept in mind throughout the whole study and finally briefly analyzed in the discussion.

Helpful guidelines for a conceptual framework of Sustainability Assessment and the development of criteria and indicators underlying a top-down, principle based approach were found to be presented in Ritchie et al. (2000: 14). They present a conceptual framework with a hierarchy of principles, criteria, indicators and verifiers. Their definitions and procedure were taken and adapted to the purpose of this study. For reasons of simplicity verifiers were not used in this study. The framework from Richtie et al. (2000: 14), defines principles as top-level statements or fundamental truths, which embody human wisdom. They are usually expressed as statements of ideals and form the umbrellas under which all criteria and indicators fall. Criteria are standards by which progress towards meeting the principles can be judged. They are reflections of knowledge and they add meaning to the principle and make them more functional by defining the particular state or condition that we would expect to see if the principle is adhered to. Indicators are the components or variables of the management system that imply or indicate the state or conditions required by a criterion. Indicators are usually stated as something specific that can be assessed in relation to the criteria. The criteria and indicators for sustainability need to be considered in and adapted to the local context in which they are to be used (Ritchie et al. 2000: i). Ritchie et al. (2000: 28) suggest it to be a well-recognized starting point, to start with a set of criteria and indicators which have already been developed and by changing and modifying them to make them become appropriate and relevant to local circumstances of the study.

Sustainability indicators should cover the three pillars and include environmental quality, economic performance and social suitability. Indicators can be used individually, as part of a set, or in the form of a composite index, whereby individual indicators’ scores are combined into a single number. Indicators should be clear and single-valued, coherent and consistent (logical), appropriate in scale, sufficient in information, capable of linking different aspects (exclusiveness and exhaustiveness), measurable and have available data or data collection methods for each of the indicators, based on easily obtainable information, be quantitative, monetary and non-monetary, non-overlapping and encompass a given time period, be disaggregated on the national or even regional level, relevant to the activity’s description, reproducible, and comprehensible to those without specific knowledge (Carrera and Mack 2010: 1031, Dantsis et al. 2010: 257). Although it is difficult for every indicator to conform to all these requirements, it is important that they adhere as far as possible (Dantsis et al. 2010: 257). This study will select one indicator for each dimension and try to adhere to these selection criteria for choice of indicator. Of course one indicator will not be able to cover all aspects of the dimension; nonetheless it is meant to be representative for the most important aspects of its dimension.

Some of the environmental indicators found in literature review include crop variety, biomass production (OECD 2001: 299, 315), crop diversity, use of fertilizers, use of pesticides, irrigated water consumption, farm management practices such as agro-ecological management practices (Dantsis et al. 2010: 257), trees survival and growth rate (Critchley et al. 1991: 7.3.6). For this study also water efficiency, expressed in output per unit of cubic meter of water input (Harvey and Reed 2004: 9) or irrigable area per season might be a relevant indicator. Economic indicators found in the literature appropriate for the scale of this study where farm productivity and variability of income (Dantsis et al. 2010: 257). Furthermore household revenue, revenue per area and cost-benefit (same as net benefit or the result of cost-benefit ratio) could be suggested by this study. Revenue per cubic meter of water would be a combined economic and environmental indicator. Regarding social indicators Carrera and Mack (2010: 1031) acknowledge that the tradition of social indicator research has always been guided by the questions of how to measure ‘‘quality of life’’ and how influencing factors can be adequately assessed. Dantsis et al. (2010: 257) suggest that gardeners’ self-reliance which may contribute to the retention of the agricultural population in the countryside is the main pre-condition of sustainability. Indicators found in use are agricultural employment and health effects (Carrera and Mack 2010: 1031). Other indicators of social sustainability might be the level of risk taken, e.g. size of cropping area determined by the level of probability of rainfall accounted with each year, which determined yield and risk of crop failure. Authors such as Esping-Andersen (2000) have criticized social indicator research as being merely descriptive since data is mostly collected without an underlying theoretical conception, which ideally should guide the selection of criteria and indicators. This problem is predominant since there is no widely accepted overarching societal theory that allows delineating social indicators for the measurement of social impact (in Carrera and Mack 2010: 1031). This study will focus on the concept of quality of life and human well-being of which human health is an important aspect. An indicator will be taken, that can be clearly measured representing these factors and resulting from the social analysis of this study. The indicators will be selected after the analysis of the ecologic, economic and social implications of rainwater harvesting in combination with gardening, in chapter 5.2.

4.2 Procedure

The procedure of this study is described in the subsequent section and schematically presented in Figure 23.

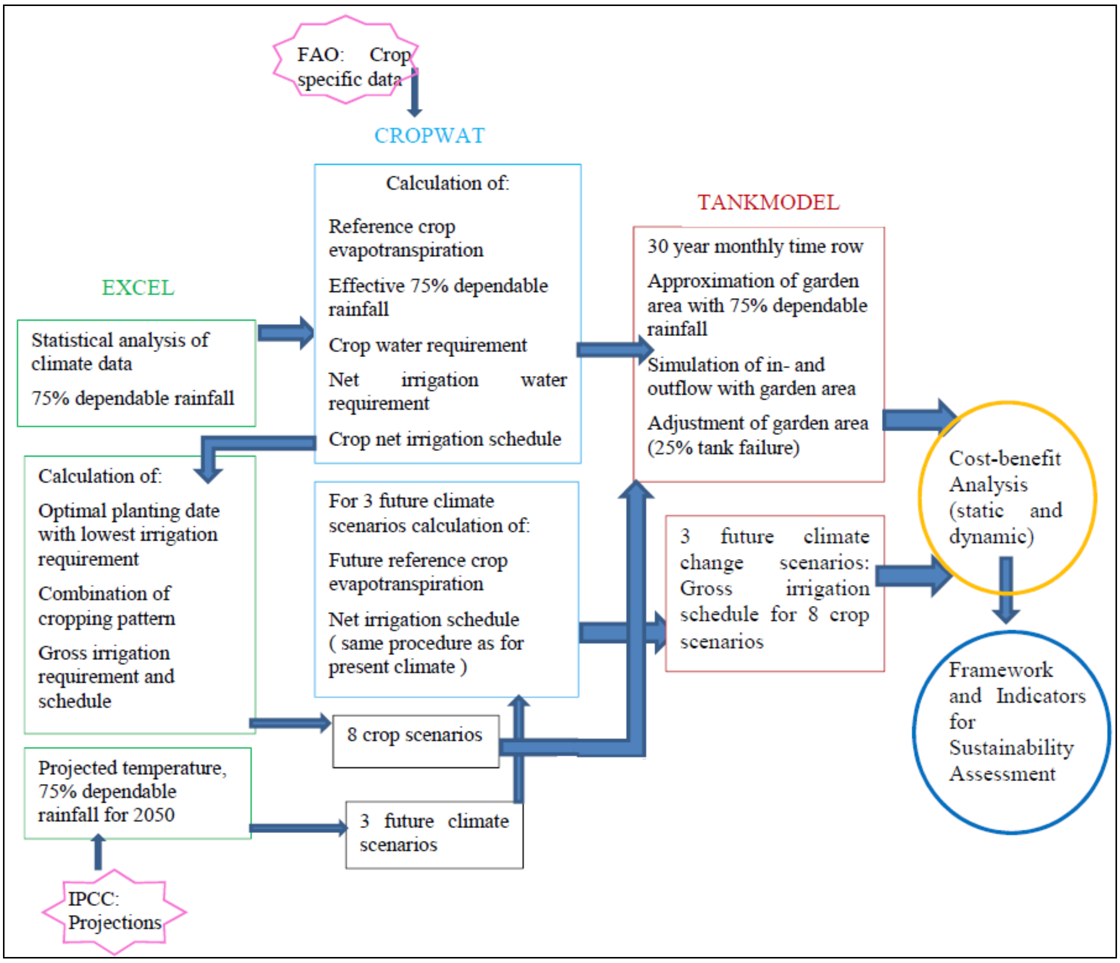


Figure 23: Schematic procedure of the study

A tank model of the rainwater harvesting tank was created with Excel to model monthly inflow and outflow. For the calculation of tank inflow, a monthly time row was constructed by listing monthly precipitation amounts from the last 30 full available years. Since after Namibian independence precipitation was not recorded regularly, nearly half of data is missing and therefore data of the 30 last available years ranges back from January 1950 to December 2008. Then monthly tank inflow was calculated by multiplying the roof runoff coefficient (0.85), the roof size (100 m^2) and monthly precipitation values. These monthly tank inflow values were set against the tank outflow, monthly withdrawals for garden irrigations. To calculate tank outflow irrigation requirements were calculated. For this, first crop water requirements ET_o need to be determined, the procedure looks as follows. The following mean monthly climate data were calculated with Excel from available daily data from 2003 to 2007 (provided by the Namibian Weather Bureau) and put in Cropwat: minimum and maximum

Temperature (°C), relative humidity (%), wind speed (km/day) and length of sunshine hours (h/day), the latter taken from the Cropwat suggestion for the given geographic location (latitude of 18° S). With these climate parameters Cropwat calculated the radiance (MJ/m²/day) and the reference crop evapotranspiration (mm/day) using the Penman-Monteith method. Then Cropwat required input of monthly precipitation data, for which the monthly 75% dependable rainfall was used, previously calculated with Excel from available monthly data of the last 30 years (1950 to 2008 provided by the Namibian Weather Bureau). With the USDA S.C. Method, Cropwat computed the monthly effective precipitation. Using the single coefficient method, Cropwat required the input of location and crop specific values to adjust the K_c curve of each crop. These were length of the initial, development, mid-season, and late season mean and for each stage a variable for the K_c curve, rooting depth, critical depletion fraction, yield response factor and crop height for each stage of growth. No correction value for ET_c was used. In addition, soil data input was required, for which data suggested by Cropwat for "light sandy soil" was chosen. These include total available soil moisture (60 mm/m), maximum rain infiltration rate (40 mm/day), maximum rooting depth (50 cm), initial soil moisture depletion (0%) and initial available soil moisture (60 mm/m). Given these input data, Cropwat calculated net crop water requirements for the growth period in mm/10 days of each chosen crop. Deducting the effective dependable rainfall from crop water requirements, Cropwat calculated the irrigation requirement per crop for one m².

Then the cropping and irrigation schemes were calculated. Cropwat required the input of a cropping pattern, namely which crops are to be planted at which planting date and on which proportion of the field area. For this, 4 gardens with different criteria have been created, each with 1 and 2 annual planting seasons, resulting in 8 crop scenarios (Table 3).

Table 3: Crop scenarios

crop scenario	1 annual planting season	2 annual planting seasons
subsistence	A1	A2
cash	B1	B2
low water	C1	C2
high risk	D1	D2

Crop water requirements for the entire growth period of each crop depending on planting date were assembled with Excel. The optimal planting date for each crop combination which consumes the least amount of water with 1 and 2 annual planting seasons were calculated with Excel. In addition, it was controlled if the most water efficient planting date for each crop matches planting periods suggested by the FAO (Savva and Frenken 2002b: 27 to 43) in terms of temperature and seasonality. Best cropping pattern for each scenarios where assembled according to the above parameters, including optimal planting date and choice of crops to grow. Finally, gross crop irrigation requirement was calculated with Excel, assuming irrigation efficiency of drip irrigation with 0.75. For each crop cultivable in Namibia according to Price Waterhouse Coopers (2005: 13) the market price and yield were assembled and the water use [m^3/m^2] was calculated with Excel with data previously calculated with Cropwat.

The garden area of each crop scenario was approximated depending on irrigation capacity. For this, the quantity of yearly harvested rainwater in the 30 m^3 tank was estimated, assuming 75% yearly dependable rainfall falling in 3 out of 4 years. This data was taken from the statistical analysis of precipitation from 1950-2008. The approximated area of each cropping pattern was tested with the tank model on the 30 year time series with precipitation amounts that actually occurred during that period. It was tested how often the tank would have run dry and yield would have failed. The area and therefore the gross irrigation requirement was then adjusted, usually enlarged, so that against the 30 year time series the tank would have run dry with a frequency of 25%, according to the 75% dependable rainfall used for calculation of irrigation requirements. The occurrence of 25%tank failure was rounded from 7.5 out of 30 years to 7 out of 30 years. This frequency was chosen by considering the trade-off between reaching a high benefit from gardening produce and maintaining an acceptable risk of crop failure. On one hand, if a large area is planted with a high possible yield, benefits can be high and available water is used to a maximum extend, while little excess water remains unused for crop irrigation; in turn risk is high that the tank runs dry in an elevated amount of years and there is an increased frequency of crop failures. On the other hand, planting a smaller area which possibly reaches a lower yield signifies a smaller risk that the tank runs dry and crops fail, however in turn this area reaches a smaller annual benefit and in years of high rainfall a great proportion of the water remains unused for gardening. Considering these trade-offs the probability of the tank to run dry in 25% of years seems acceptable balance between risk taken, achievable benefit and unused water.

Then, by looking at the tank model of the 30 year time series, it was determined how much of gross crop irrigation requirement can be satisfied each year with the given area. This can be expressed in a graph showing the amounts of years in which gross crop water requirement can be fully satisfied and the degree of satisfaction in the remaining years. For years when the tank runs dry, economic loss resulting from crop failure, amount of supplemental water needed for irrigation as well as the costs to buy tap with quantity from tap water were calculated. In these years, when tank runs dry, measures need to be assumed. One measure could be the purchase of tap water. The purchase of tap water was compared to the possible economic loss from crop failure. The option recommended by this study is the one with the lower costs. An alternative measure might be an early adaptation of the cropping area so that water will be sufficient over the whole growth period. This could be i.e. the ratio of rainwater harvested in the tank to water monthly withdrawal.

Gardening area was also estimated for future changing climate conditions until 2050, the end of the life span of the rainwater harvesting facility. For this, possible climate scenarios were created using seasonal data of climate change projections from 21 models considered by the IPCC (2007). For the purpose of this study, three scenarios were established in order to cover the full range of uncertainty, namely (1) a best case scenario with minimum temperature increase and minimum precipitation decrease, (2) a medium case scenario with the median temperature increase and the median precipitation decrease, and (3) a worst case scenario with maximum temperature increase and maximum precipitation decrease (Table 4). Since all of the 21 models considered by the IPCC are equally valid and with no assigned probabilities of occurrence (Nakicenovic and Swart 2000), the three established scenarios are also considered to be equally probable.

Table 4: Temperature and precipitation input for three future climate scenarios for 2050

Future climate scenario	Response (%)	
	Temperature	Precipitation
Best case	minimum	maximum
Medium case	median	median
Worst case	maximum	minimum

Taking the data provided by the IPCC (Christensen 2007: 854) and previously exposed in chapter 3.2, future monthly precipitation and temperature change was calculated for the three scenarios until 2050. Since the IPCC (Christensen 2007: 854) indicates climate data projections for the period 2090 to 2099, and the signal is assumed to increase linearly in time, 2/3 of the response is subtracted from the value, in order to calculate data projections for 2050.

Future crop water requirements for the 3 climate scenarios for 2050 were projected with Cropwat using the corresponding projected temperature (minimum and maximum) and precipitation (75% dependable rainfall) for the given climate scenario. The other required parameters humidity, wind speed and length of daily sunshine were not consider for the projection of crop evapotranspiration with Cropwat, due to the lack of projections until 2050. In reality these parameters are expected to change, as for instance humidity will change as a consequence of changes in temperature, precipitation and cloud cover. Daily sunshine hours might change as a consequence of changes in cloud cover and wind speed might change for instance due to weakening monsoon rains.

On the basis of these results, new irrigation schedules for the 3 climate scenarios for 2050 and for the 8 crop scenarios were calculated, using the same planting dates as under present climate. The 30 year time series from 1950 to 2008 of the tank model was adapted with the given projected precipitation change for each future climate scenario. Then, the 8 crop scenarios with the area of 2010 were tested for all future climate scenarios on the 30 year time series. The frequency of tank failure under changed climate conditions was counted as well as annual degree of satisfaction of irrigation requirement was calculated. For years when the tank runs dry, again economic resulting from crop failure, quantity of supplemental water needed for full satisfy irrigation requirements and costs to purchase tap water were calculated for each future climate and crop scenario. For each year it was determined if the economic loss or the costs to purchase tap water would be superior.

Finally, a new area was determined for each of the8 crop scenarios under the 3 future climate scenarios was determined having the same risk of crop failure due to lack of harvested water as under present climate (25%). For this, the area was firstly estimated with the 75% yearly dependable rainfall for 2050 under the respective future climate scenario and then adjusted to the actual 30 year time series, adapted to the future climate projections, so that the tank runs dry in 7 out of 30 years.

As a further step, an economic cost-benefit analysis was done to estimate profitability, using two different methods: the static pay-back and dynamic net present value method. First, different tanks were compared for their profitability under the 8 crop scenarios. Then the most profitable tank was tested for its profitability comparing future climate scenarios for different crop scenarios.

In order to determine the sustainability of the 8 crop scenarios, one indicator for each sustainability dimension was chosen. These indicators are not meant to cover all aspects of the relative dimension, but are rather intended to be a meaningful representative for economic, environmental and social aspects. The scenario reaching the best values for all the three indicators is considered to be the best option. All three indicators are considered to be equally important.

5 Results of the study

5.1 Modeling the rainwater harvesting system

5.1.1 Tank balance

In order to estimate the quantity of harvested rainwater available in the tank for meeting irrigation demand, a monthly tank balance has been set up with Excel. Tank inflow (tank $_{in}$) is the precipitation, while the water extracted for crop irrigation is the tank outflow (tank $_{out}$). This model was run to determine the area that can be irrigated with the harvested rainwater under different cropping and climate scenarios and to test how often the tank runs dry. The tank balance is sketched in Figure 24 and expressed in Equation 9.

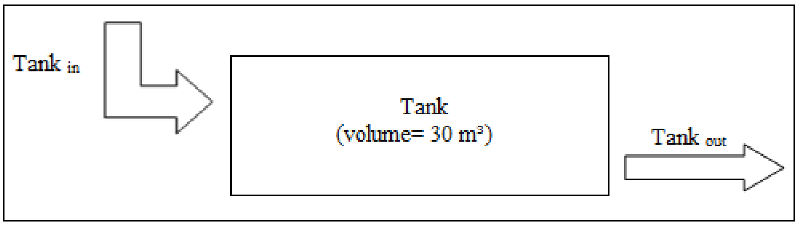


Figure 24: Rainwater harvesting tank model

Equation 9: Tank water balance

$$\boxed{\text{Tank}_{t1} = \text{Tank}_{t0} + \text{Tank}_{in\, t1/t0} - \text{Tank}_{out\, t1/t0}}$$

Where:

$\text{Tank}_{\text{in t1/t0}}$ = monthly harvested rain

$\text{Tank}_{\text{out t1/t0}}$ = monthly gross irrigation requirement [m³]

Tank_{t1} = water stored at month t_1

Tank_{t0} = water stored at month t_0

The runoff coefficient for iron sheet roofs is with 0.85 fairly high, meaning that 85% of precipitation falling on the roof flows into the tank (Sturm et al. 2009: 777).

5.1.2 Tank inflow

Monthly harvested rain or tank inflow is calculated, by multiplying the actual monthly rainfall from the time row of the last 30 available years (1950 to 2008) with the runoff coefficient for roof catchments (0.85) with the catchment size (100 m²), as shown in Equation 10.

Equation 10: Monthly tank inflow (Sturm et al. 2009: 780)

$$\boxed{\text{monthly tank inflow}\,[\text{m}^3] = \text{monthly precipitation}\,[\text{m}] \bullet \text{roof catchment size}\,[\text{m}^2] \bullet \text{runoff coefficient}}$$

5.1.2.1 Statistical analysis of precipitation

Available precipitation data of the last 30 years for the period 1950 to 2008 from Ondangwa station, around 30 km from Epyeshona village, has been statistically analyzed, a summary is presented in Table 5. Mean monthly precipitation, standard deviation, minimum and maximum precipitation, the range of monthly observed precipitation as well as monthly precipitation levels at different probability levels were computed.

Table 5: Statistical analysis of precipitation at Ondangwa station from monthly data 1950-2008 (Namibian Weather Bureau)

n	month	mean precipitation [mm]	Standard deviation (Ϭ)	min. precipitation [mm]	max. precipitation [mm]	range [mm]	precipitation [mm] at probability level [%]				
							90	75	50	25	10
30	January	111.7	69.2	7.2	271.4	264.2	33.4	60.4	98.2	148.2	208.9
30	February	108.9	80.3	8.2	315.8	307.6	22.9	49.5	97.5	119.8	251.7
30	March	84.8	65.4	8.9	241.3	232.4	27.2	31.0	70.4	116.7	181.6
30	April	31.2	28.8	0.0	105.2	105.2	2.9	6.2	23.2	49.0	76.7
30	May	3.2	10.4	0.0	56.4	56.4	0.0	0.0	0.0	0.8	6.5
30	June	0.5	1.5	0.0	6.5	6.5	0.0	0.0	0.0	0.0	0.3
30	July	0.0	0.1	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.0
30	August	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
30	September	0.7	1.9	0.0	8.3	8.3	0.0	0.0	0.0	0.0	1.7
30	October	14.9	17.8	0.0	63.8	63.8	0.0	0.8	8.9	21.5	42.3
30	November	47.3	41.8	1.1	169.0	167.9	11.1	19.7	34.2	59.6	119.6
30	December	61.2	51.1	1.7	227.3	225.6	5.0	11.6	52.3	95.8	112.2
30	Annual	464	202.4	201.7	1038.6	836.9	261	333.9	381.5	578.4	703.9

The distinctive rainy season begins in October and ends in April, with 80% of the rainfall usually occurring from December through March. During the dry season from May to September practically no rainfall can be expected in 9 out of 10 years (see also Figure 26). The highest variability is to be expected in February, with a standard deviation of 80 mm, meaning that in about 68% of years the precipitation varies between 29 and 189 mm. Overall the interannual variability is high, especially during the rainy season from December through March, with variations ranging from 225 to 310 mm per month. Probability analysis shows that mean annual precipitation falls with a probability of 38%, meaning every 2.6 years or in 3.8 years out of 10. Figure 25 shows the pobability of occurance (%) of annual precipitation levels.

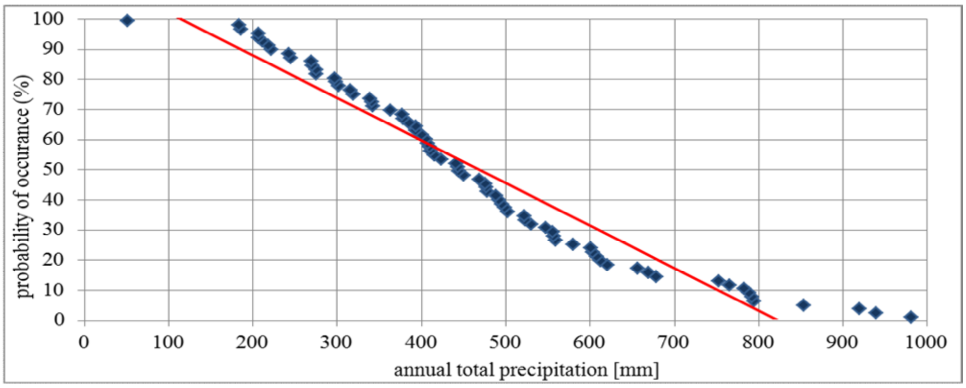


Figure 25: Probability of occurrence of annual precipitation at Ondangwa station [%] (own calculation, data source: Namibian Weather Bureau)

Monthly precipitation was analyzed with the statistic program R 2.11.0 through a boxplot illustration. Figure 26 illustrates the smallest observation, the 0.25 quantile, the median, the 0.75 quantile and the largest observation as well as outliers, indicated with circles for each month for the time period 1950 to 2008.

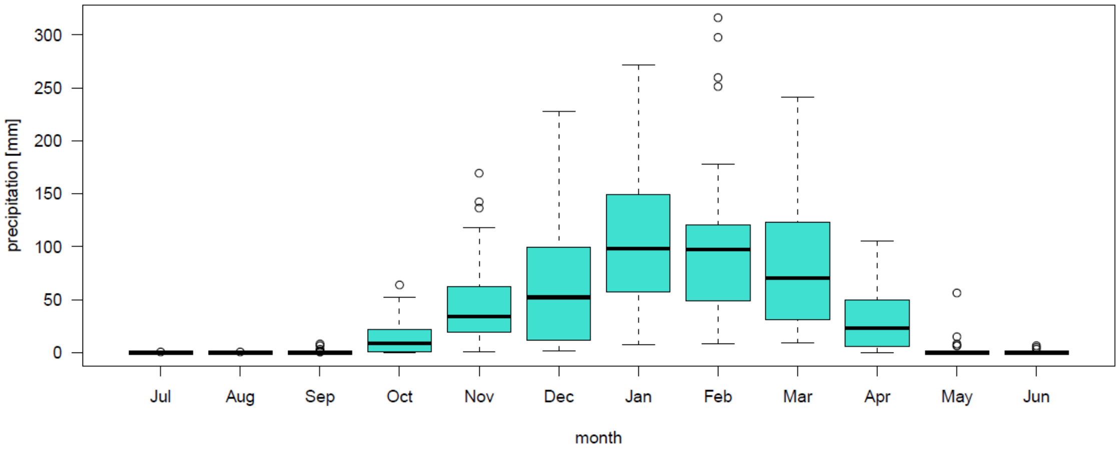


Figure 26: Monthly precipitation [mm] at Ondangwa station from monthly data from 1950-2008 (own calculation, data source: Namibian Weather Bureau)

The months May through September have maximum precipitation values of 0 mm, values above are considered to be outliers. January and February have the highest median precipitation which is both about 98 mm. However, for January the 0.25 quantile reaches 148 mm, while for February it is significantly lower with 120 mm. Precipitation values for the month December to March are highly variable, 50% spreading around the median with a range of 70 to 88 mm.

As illustrated in Figure 27, most complete precipitation data concerns the years 1935 to the 1970s. However, from the 1980s and especially around independence to the year 2000 data is regularly missing and turned to be recorded regularly only from the year 2003. Mean annual precipitation, calculated from available data for the period 1902 to 2009 was 473 mm. High inter annual variability is expressed through a high standard deviation of 202 mm, meaning that 68% of annual precipitation data ranged between 675 mm and 271 mm. The linear trend line (red) of annual precipitation amounts shows that precipitation has already been decreasing since 1902. This is confirmed by the linear regression t-test presented in the following paragraph. The 10 year running mean calculates the mean value of the last 10 available years (not of the 10 last available values), if data was not available for some years the mean value of fewer years was taken. The 10 year running mean indicates a periodicity of two wet and two dry alternating cycles, each lasting about 10 to 15 years. In addition, in can be observed, that an extremely low amount of precipitation falls about every 10 years. Fully available data of the last 30 years encompasses the period 1950 to 2008. The years 2004 to 2008 have all annual precipitation values which are clearly above the mean, with the exception of the rainy seasons 2004/05 and 06/07 which are slightly below the mean.

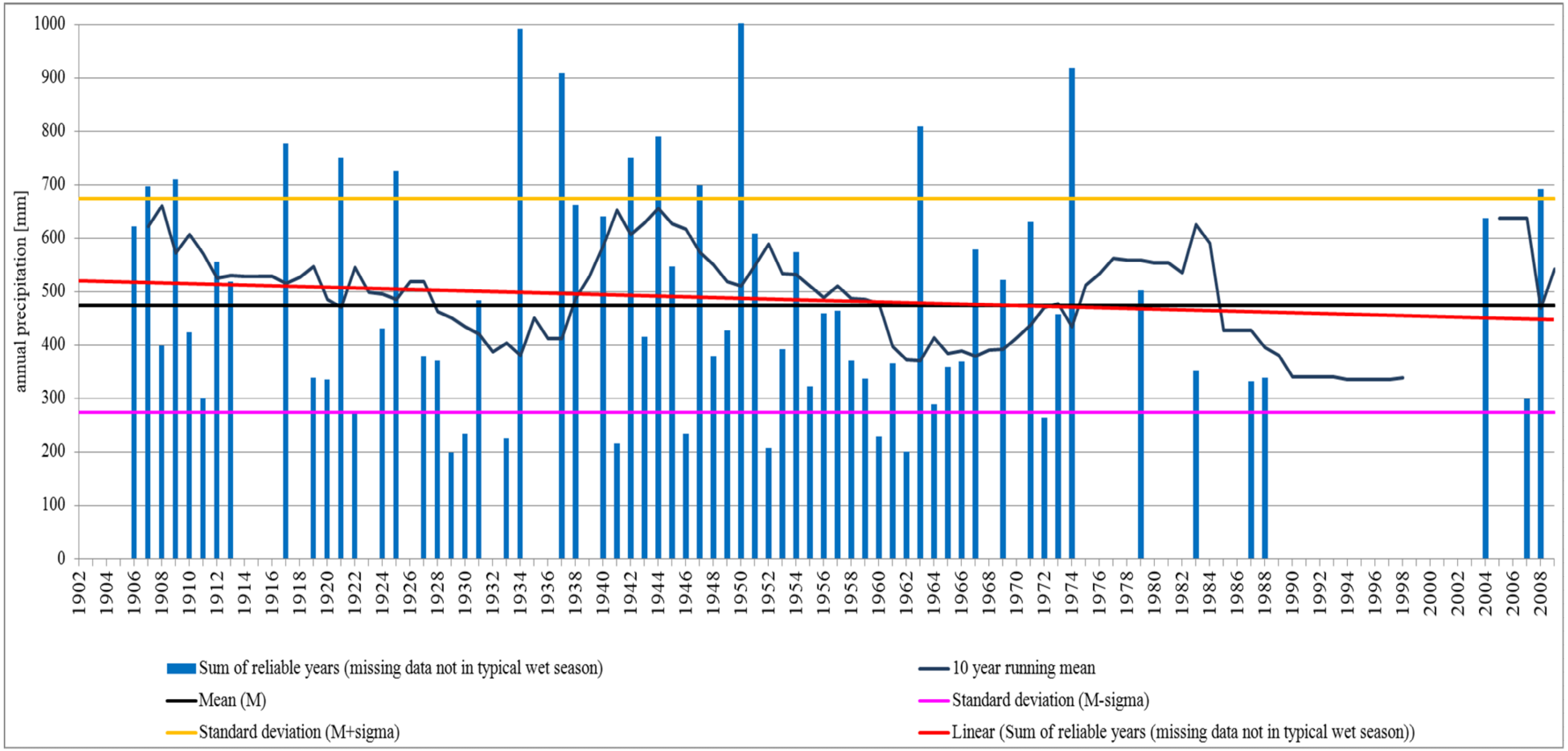


Figure 27: Annual precipitation [mm] of years with reliable data at Ondangwa station (from monthly data 1902-2009, data: Namibian Weather Bureau)

The linear regression t-test was used in order to determine whether the slope of the regression line differs significantly from zero. Therefore the null hypothesis was tested, which states that the slope is equal to zero, or in other words annual precipitation has not changed from 1902 to 2009. The p value, the probability of observing a sample statistic as extreme as the test statistic, has resulted to be p = 0.00502. Therefore the p-value is below the 5% and 1% significance level (p> 0.05 >0.01). This means that the null hypothesis can be rejected, with a significance level of 1%. As a result, there has been a statistically significant change in precipitation (a decrease) from 1902 to 2009. This shows that climate change has already taken place and precipitation has already been decreasing in the past century. Only in 1% of cases such values can be observed by chance, which would mean that precipitation has actually not decreased. Indeed, as shown in Figure 27, the red regression line shows a decrease in mean precipitation by around 60 mm (from around 520 mm to 460 mm) since 1902.

5.1.3 Tank outflow

5.1.3.1 Analysis of other climate data

Other relevant climate data analyzed include minimum, maximum and mean temperature and humidity. They are put in relation with potential evapotranspiration and 75% dependable rainfall. Temperatures are the highest from October to March, when minimum temperatures range between 19°C to 21°C and maximum temperatures from 31°C to 35°C. The coolest season is the period from May to August, when minimum temperatures reach 10°C to 12°C and maximum temperatures are as high as 27°C to 31°C (Figure 28).

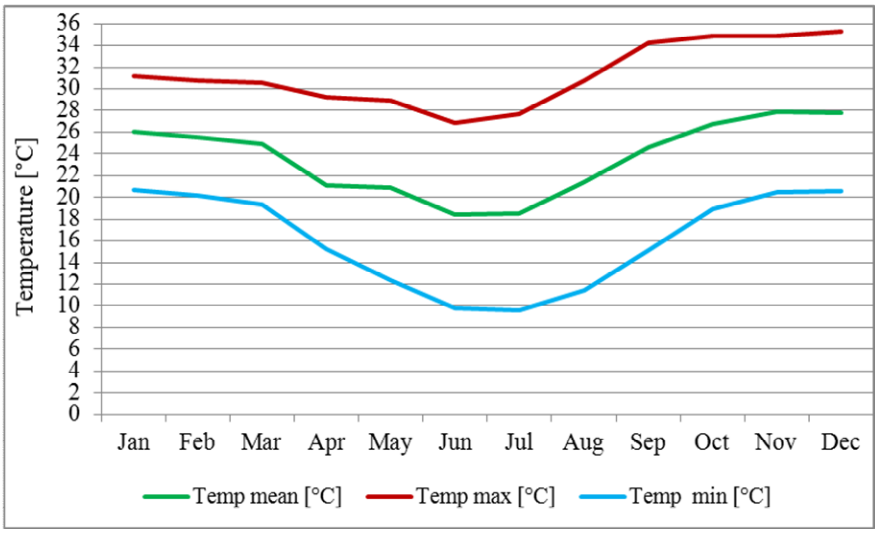


Figure 28: Temperature [°C] at Ondangwa Station (from daily data 2003-2007) (own arrangement, data source: Namibian Weather Bureau)

Calculated annual reference crop evapotranspiration under present climate is 1,891 mm, computed with available data of the years 2003 to 2007. Reference crop evapotranspiration ET_o is the highest during the hottest months from September to March, being between 151 and 230 mm/ month, when mean temperature is between 25°C to 28°C and relative humidity between 20% to 64%. During the winter months from May to August ET_o is lower, ranging between 89 and 150 mm/ month, due to lower temperatures (18°C to 21°C) and less daylight, with levels of relative humidity between 245 to 36% (Figure 29).

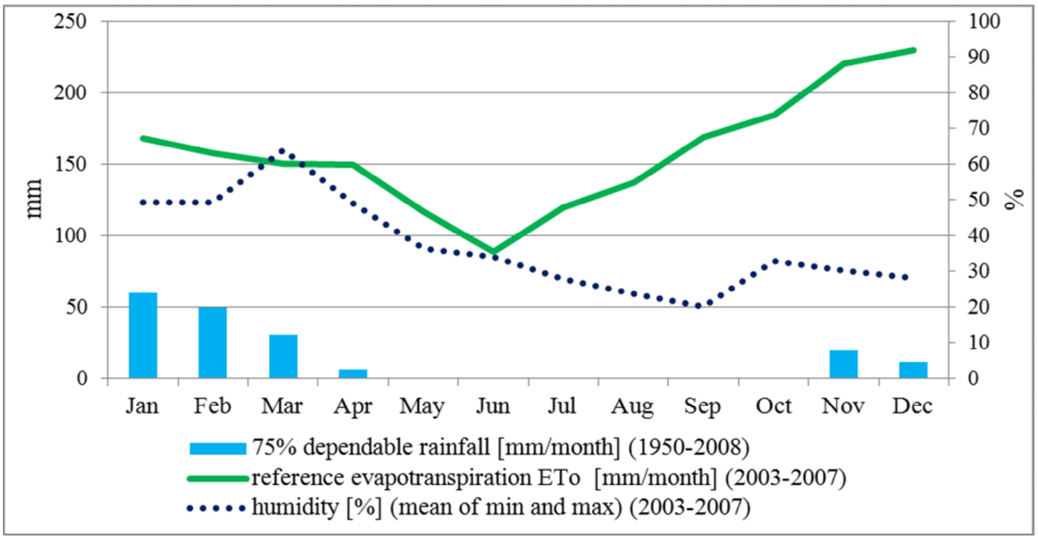


Figure 29: Relative humidity, crop evapotranspiration (from daily data 2003 to 2007) and 75% dependable rainfall (1950 to 2008) at Ondangwa station (own arrangement and calculation, data source: Namibian Weather Bureau)

Literature indicates a potential evaporation of around 2600 mm (Heynes 1995: 470). In comparison to this, the calculated data of evapotranspiration is considerably lower. For this reason the results for reference crop evapotranspiration ET_o at Ondangwa station were compared to data from other meteorological stations with similar climates, rainy seasons and geographic proximity, provided by the FAO (Climwat) and by Savva and Frenken (2002a: 22, 69) (Figure 30). As can be seen in Figure 30, own calculated results of reference evapotranspiration match with those of these comparable stations, regarding seasonality and amplitude of monthly values. In addition, the FAO (Allen et al. 1998) indicates $Et_{o,}$ for subtropical semi-arid regions, to be 4 to 6 mm/day for mean temperature around 20°C and 6 to 8 mm/day for temperatures above 30°C. These are in line with calculated daily ET_o values of this study, with the exception of June were the calculated value of this study is slightly below the indicative FAO value with 2.96 mm/day, with mean a temperature of 18°C (minimum 10°C to maximum 27°C). The curve calculated by this study to a small extend uneven, probably due to the small data base of 2003 to 2007, but especially due to wind speed data, only available from 2007 and end 2006 with high fluctuations between the two years and the seasons. Especially the value for December seems to be too high, probably due to the high wind speed recorded in 2007, which is likely not to be representative.

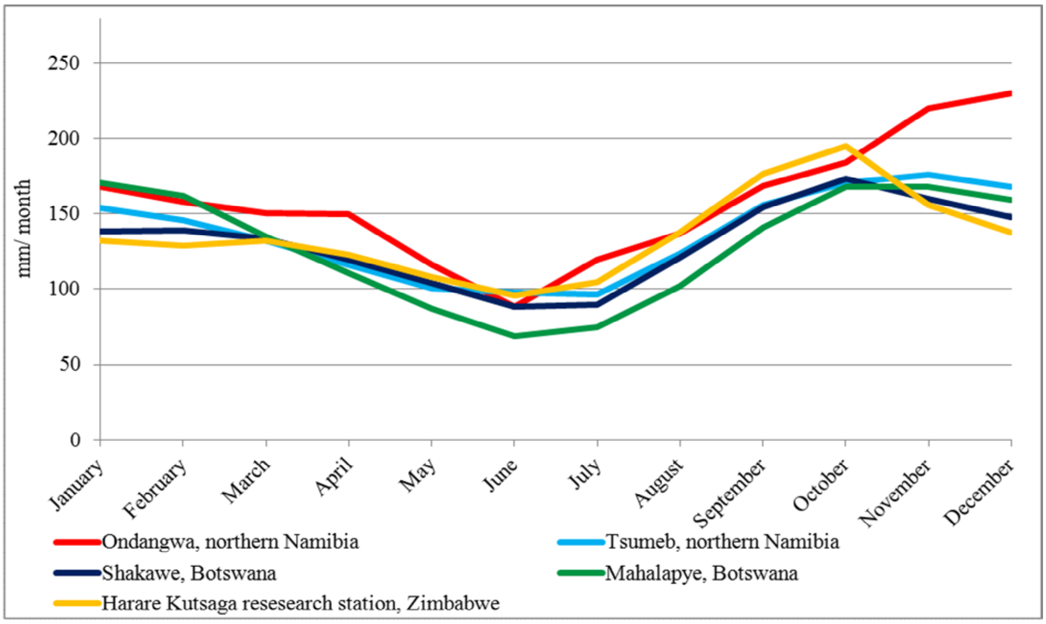


Figure 30: Reference crop evapotranspiration ETo [mm/month] at Ondangwa (17.3°S, 15.98°E, 1100 m) station and comparison of results with other stations with similar semi-arid climates: Tsumeb, northern Namibia (19.23°S, 17.71°E, 1311 m), Harare Kutsaga research station, Zimbabwe (18°S, 31.2°E), Shakawe, Botswana (18.36°S, 21.85°E, 1000 m) and Mahalapye, Botswana (23.05°S, 28.05°E, 1006 m) (Ondangwa: own calculation with Cropwat, data source: Namibian Weather Bureau. Tsumeb and Shakawe: FAO Climwat. Kutsaga and Mahalapye: Savva and Frenken 2002a: 22, 69)

5.1.3.2 Crop water requirement

Withdrawal of harvested rainwater is intended to be used for gardening activities. Gardening products are high value fruit and vegetables, such as tomatoes, cabbages, potatoes, carrots, lettuce, cucumber, beans, zucchini, cauliflower, onions and watermelon, mangos, avocados, citrus, dates, olives. These are all cultivable in northern Namibia under local conditions (Price Waterhouse Coopers 2005: 13). If consumed domestically they help to enrich the diet, if sold at markets they can generate additional income. The output of a garden depends on its size and the amount of water available. In addition, there is the possibility to plant during one, two or three seasons a year. Since during the dry season in northern Namibia from May to September there is practically no rainfall, crops which are grown off-rainy season highly depend on stored rainwater. Different criteria for the choice of crops include crop water requirement per area and season, yield (kg per area), value at market prices and preference of the local population. The choice of the crop with a specific water requirement influences the size of the cultivated garden area given an annual amount of harvested rain. Furthermore, if only one season is to be planted, an optimal growth period in the rainy season can be chosen. Taking maximum advantage of precipitation, not as much water for irrigation is needed, and the garden area can be larger. On the contrary, if two cropping seasons are chosen, growth periods are within the rainy season and the dry season. Consequently, more water is needed for irrigation and only a smaller area can be cultivated, meaning that also garden output will be lower. On the other side, off-rainy season vegetables and fruits achieve higher market prices and earn or save more income.

Crop water requirements were calculated using the FAO crop coefficient method. Principal crops assessed include horticulture crops and fruit trees: watermelon, lettuce, cucumber, cabbages, tomatoes, zucchini, millet, potatoes, peppers, cauliflower, onions, beans, citrus, mango, avocado, olive, date palm. Table 6 presents data input into Cropwat (white) and data calculated by Cropwat (grey). The location input is; altitude 1100 m over sea level, latitude 17.93°S, and longitude 15.98°E.

Table 6: Monthly data for calculation of crop evapotranspiration Et_0 and effective precipitation (own arrangement with CROPWAT 8.0, data source: Namibian Weather Bureau)

Month	Min. temperature [°C]	Max. temperature [°C]	relative humidity (mean of daily maximum and minimum) [%]	Wind [m/s]	Sun [hours]	Radiation [MJ/m²/day]	Reference crop evapotranspiration ETo [mm/day]	75% dependable precipitation [mm]	Effective Precipitation from 75% dependable rainfall [mm] (USDA Method)
January	20.7	31.1	49	1.5	7.8	22.8	5.61	60.4	54.6
February	20.1	30.8	49	1.3	7.8	22.4	5.26	49.5	45.6
March	19.4	30.6	64	1.9	7.9	21.2	5.02	31	29.5
April	15.2	29.2	49	2.1	9.1	20.6	4.99	6.2	6.1
May	12.3	28.9	36	1.2	10	19.2	3.88	0	0
June	9.8	26.9	34	0.8	10	17.9	2.96	0	0
July	9.5	27.7	28	1.6	10.4	18.9	4.0	0	0
August	11.4	30.8	24	1.4	11.2	22.2	4.57	0	0
September	15.1	34.2	20	1.4	11.5	25.5	5.62	0	0
October	18.9	34.9	33	1.4	10.5	26	6.15	0.8	0.8
November	20.5	34.9	30	2.2	10	26.1	7.34	19.7	19.1
December	20.6	35.3	28	2.2	10.5	27.1	7.66	11.6	11.4
Average	16.1	31.3	37	1.6	9.7	22.5	5.25		
Sum (year)							1891	179.2	167.1

Savva and Frencken (2002 b) present agronomic aspects of vegetable crops for climate conditions prevailing in Zimbabwe which can be considered comparable to those in northern Namibia. Warm season crops are zucchini, cucumber and watermelon. Potatoes can be planted throughout the year and onions require cooler conditions during the first growth period. Optimum growth occurs for peppers between 24°C to 30°C, for potatoes and tomatoes between 15°C to 20°C and cabbages between 18°C to 24°C. For peppers and potatoes only poor growth occurs when day temperatures are above 32°C, while for zucchini the temperatures should not exceed 25°C by day. Due to these factors, the period between September and December is least suited for cultivation, since maximum temperatures are above 34°C and mean temperatures above 25°C (Savva and Frencken 2007b: 27-43). As a consequence of high temperatures, reference crop evapotranspiration ET_0 in this period is the highest of the year and crop water requirements are the highest too.

Four cropping patterns have been set up, each has been varied with one and with two annual planting seasons. These scenarios help to determine size of planting area, irrigation requirement, yield and market revenue. Scenarios were created according to the following criteria: (A) subsistence farming, (B) farming in order to achieve high economic benefit while spreading risk through cultivation of several crop types, (C) planting of most water effective crops requiring the least amount of water per area, and finally (D) planting only one type of crop which combines highest achievable market price and lowest water use, in order to maximize economic benefit at a fairly high risk since there is no differentiation in produce. For scenarios A to C it was chosen to plant one tree per garden, however for D no tree is included, since trees consume considerably more water, achievable yield is relatively low and the produce only achieves low market prices. Story lines are presented in Table 7.

Table 7: Story lines of cropping scenarios

Scenario	Story Line
A subsistance garden	The produce solely serves to satisfy household consumption needs. It produces a variety of high nutritional value crops, such as vegetables and fruit (cucumber, cabbage, peppers, tomatoes, potatoes, watermelon, orange). It combines a healthy diet with saved income.
B cash garden	The cash garden aimes to maximize revenue from market sale. Crops grown (cucumber, lettuce, watermelon, mango) combine high market prices with high yields and low water requirements in order to maximize revenue. With four crops grown the diversification and risk are medium.
C low water garden	The low water garden aims to obtain a great cropping area and as a consequence a high yield. Market prices are not considered. The diversification is fairly high, with six crops (onions, squash, cucumber, lettuce, watermelon, avocado) and therefore risk fairly small.
D high risk garden	The high risk garden has a low diversification of crops. It chooses those that combine high market prices, high revenue and low water requirement in order to maximize benefits. It most rapidly covers investment costs.

In order to select the crops to cultivate under each scenario and determine optimal planting dates, irrigation requirement of the entire growth period of each crop have been calculated with Cropwat for planting on the 1st and the 15th of each month. The results are assembled in Figure 31.

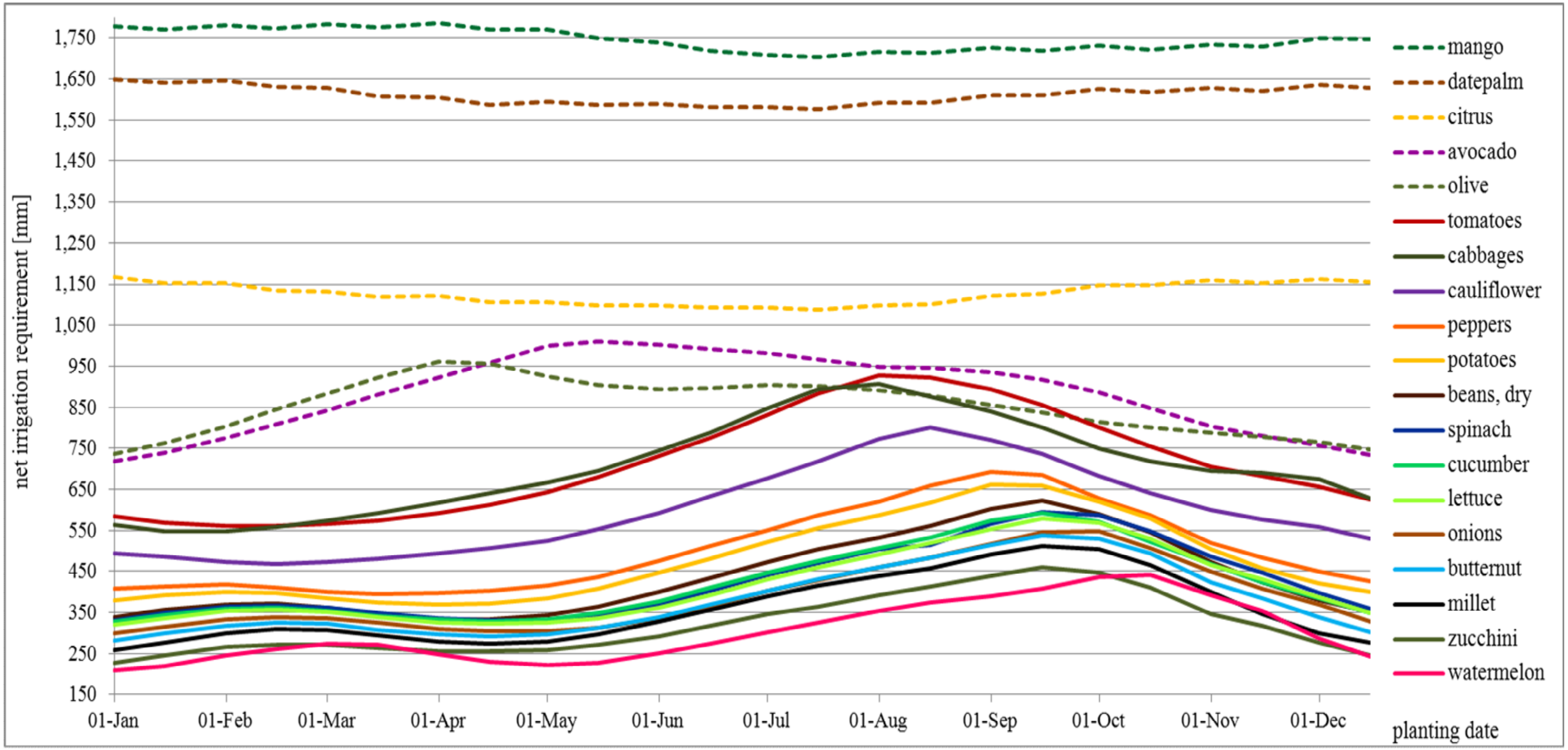


Figure 31: Crop water need [mm], equal to the total net irrigation requirement [mm], over the growth period for different crops depending on planting date, calculated with 75% dependable rainfall (own calculation with Cropwat, data base: climate data for 1950-2008 from the Namibian Weather Bureau, crop specific data from Savva and Frencken 2007a)

It results, that given the present climate in the project region, fruit trees such as mango and datepalm have by far the highest net irrigation requirement with over 1,600 mm per m² and year, since they need to be irrigated over the whole year. Avocado and citrus trees have with annual 881 mm and 1,127 mm per m² lower irrigation requirements. Horticulture crops with the lowest crop water requirement are (per growth period): watermelons (281 mm), zucchini (319 mm), millet (356 mm), onions (388 mm) and lettuce (412 mm). Tomatoes (708 mm) and cabbages (702 mm) have relative high irrigation requirments. These mean annual values differ considerably depending on the planting date, as previously described in chapter 4.1.1.3 “Estimating crop water requirement and irrigation requirement”. During the months from April to June, in the dry season when there is absolutely no rain, crop water requirements are the lowest of the year due to low temperatures. However, at the same time a considerable proportion of crop water requirements is covered by rain. It results, that calculating with 75% dependable rainfall, optimal planting period for all crops is between January 1st and February 15st. Crop evapotranspiration is considerably lower during the dry season and consequently total crop water requirements and irrigation requirements are lower. However, a smaller proportion of crop water requirement is covered by rain. This is shown with the examples of potatoe and watermelon in Figure 32 to 35.

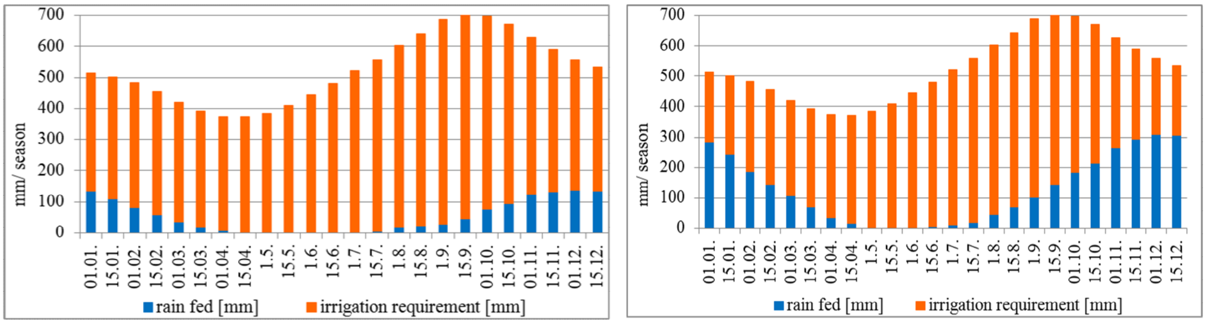


Figure 32 (left) and Figure 33 (right): Crop water requirement [mm/season]over growth period (example potatoes) depending on planting date. Proportion of irrigation requirement and rain fed. Computed with 75% dependable rainfall (left) and mean rainfall (right).

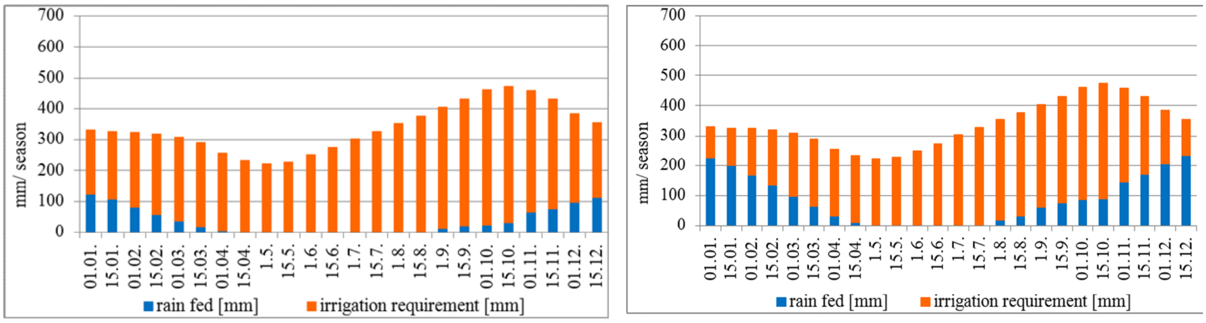


Figure 34 (left) and Figure 35 (right): Crop water requirement [mm/season]over growth period (example watermelon) depending on planting date. Proportion of irrigation requirement and rain fed. Computed with 75% dependable rainfall (left) and mean rainfall (right).

As can be seen in Figure 36 and

Figure 38 (example potatoes), irrigation requirement is the highest for planting in July to November, when on the one side crop water requirements are high due to high potential evapotranspiration and on the other side precipitation is low. Accounting with 75% dependable rain (Figure 36) lowest crop water requirements occur when the planting date is between March and June, when potential evaporation is the lowest, mainly due to low temperatures.

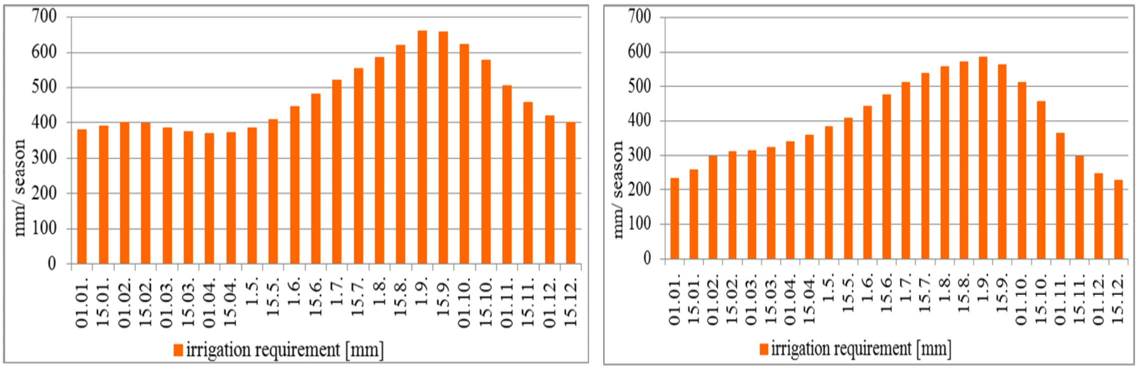


Figure 36 (left) and Figure 37 (right): Irrigation requirement [mm/season] depending on planting date. Calculated with 75% dependable rainfall (left) and with mean rainfall (right). Example potatoes.

However, planting during March and June is fairly risky, as without rain, crops completely rely on irrigation, which requires a specific quantity of harvested rainwater in the tank. Planting during the rainy season is not as risky, even if crop water requirements are higher, as they can be partly compensated with precipitation. Solely precipitation never fully satisfies crop water reuqirements, in no month and for no crop type. Assuming 75% dependable rainfall even during the months with most intense rainfall, January and February, crops need to be irrigated to satisfy crop water requirements for optimal yields. It can be concluded, that without irrigation, gardening activities are not at all possibile if optimal yield is to be achieved.

For the selection of crops and planting dates, irrigation requirement over the growth period, yield and revenue were calculated for each crop. Then, according to the criteria of each crop scenario mentioned earlier, crops and optimal planting dates were assembled. Other Factors to be considered for crop selection are site specific and include farmers’ wishes and aspirations, financial considerations, climate and soils, water availability, labor requirements, marketing aspects, availability of inputs, rotational considerations and susceptibility to diseases (Savva and Frenken 2002a: 68). A cropping pattern should consider the length of the growing season, time needed for harvest and land preparation for the next crop. According to Savva and Frenken (2002a: 68) smallholder farmers normally prefer to grow 2 to 4 crops per season so as to have a variety of crops for home consumption, to allow agronomic considerations (rotations) and also to spread their risk when it comes to marketing. To allow this, plots are normally subdivided in to 2, 3 or 4 subplots. With two crops grown on the same area per year, the cropping intensity is 200% (Savva and Frenken 2002a: 69). The results of optimal crop combination and planting dates are the eight created cropping programs illustrated in Figure 38, each forming an own independent crop scenario.

A1: Subsistence garden with one planting season

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (16%)	01-Jan	peppers		30-Apr								
Field 2 (16%)	01-Jan		tomato			04-Jun						
Field 3 (16%)	01-Jan		cucumber	15-Apr								
Field 4 (16%)	01-Jan			cabbage		14-Jun						
Field 5 (16%)	01-Jan	water melo	21-Mar									
Field 6 (16%)	01-Jan		potatoe	25-Apr								
1 tree	01-Jan					orange						31-Dec

A2: Subsistence garden with two planting seasons

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (33%)												01- Dec
	peppers		30-Mar	15-Apr		tomato			02-Sep			
Field 2 (33%)												
	01-Jan			cabbage		14-Jun	01-Jul		cucumber	13-Oct		
Field 3 (33%)												
	01-Jan	water melo	21-Mar	01-Apr		potatoe	24-Jul					
1 tree	01-Jan					orange						31-Dec

B1: Cash garden with one planting season

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (33%)	01-Jan		cucumber	15-Apr								
Field 2(33%)	01-Jan		lettuce	10-Apr								
Field 3(33%)	01-Jan	water melo	21-Mar									
1 tree	01-Jan					mango						31-Dec

B2: Cash garden with two planting seasons

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (33%)	01-Jan		cucumber	15-Apr	01-May	water melo	19-Jul					
Field 2(33%)	01-Jan		lettuce	10-Apr	15-Apr	cucumber	28-Jul					
Field 3(33%)	01-Jan	water melon	21-Mar	01-Apr		lettuce	09-Jul					
1 tree	01-Jan					mango						31-Dec

C1: Low water garden with one planting season

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (20%)	01-Jan	water melon	21-Mar									
Field 2 (20%)	01-Jan		zucchini	10-Apr								
Field 3 (20%)	01-Jan		onions	05-Apr								
Field 4 (20%)	01-Jan		cucumber	15-Apr								
Field 5 (20%)	01-Jan		lettuce	10-Apr								
1 tree	01-Jan				avocado			28-Aug				

C2: Low water garden with two planting seasons

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (20%)	01-Jan	water melon	21-Mar	01-Apr		onions	04-Jul					
Field 2 (20%)	01-Jan		zucchini	10-Apr	15-Apr		lettuce	23-Jul				
Field 3 (20%)	01-Jan		onions	05-Apr	15-Apr	water melo	03-Jul					
Field 4 (20%)	01-Jan		cucumber	15-Apr	01-May		zucchini	08-Aug				
Field 5 (20%)	01-Jan		lettuce	10-Apr	15-Apr		cucumber	27-Jul				
1 tree	01-Jan				avocado			28-Aug				

D1: High risk garden with one planting season

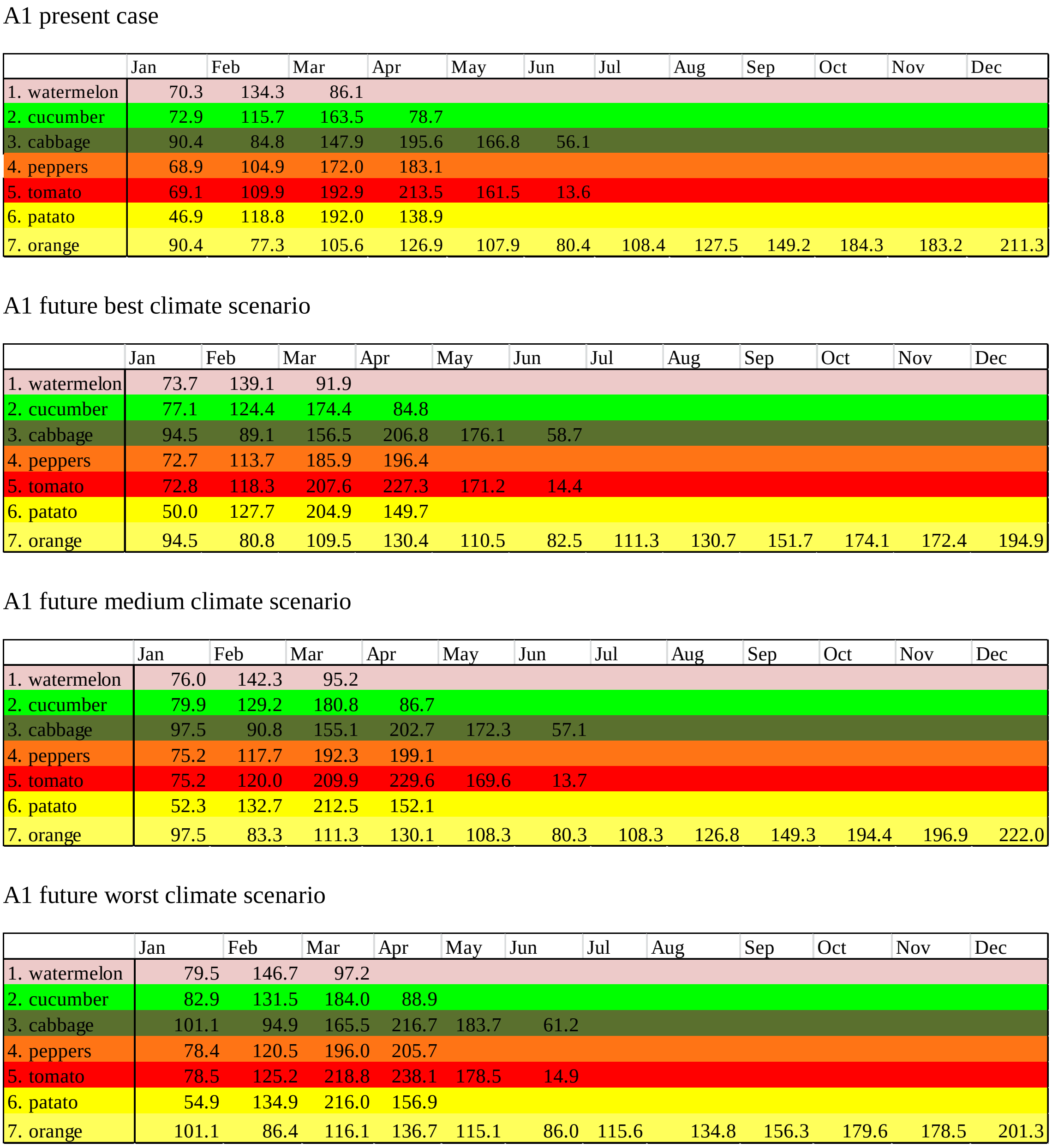
	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (100%	01-Jan		cucumber	15-Apr								

D2: High risk garden with two planting seasons

	Jan	Feb	March	April	Mai	June	Juli	Aug	Sept	Oct	Nov	Dec
Field 1 (100%	01-Jan	cucumber		15-Apr	01-May	cucumber		13-Aug				

Figure 38: Cropping patterns of 8 crop scenarios with planting and harvesting date, created under consideration of optimal planting period, lowest crop irrigation requirement for project location Epyeshona and independently from the rainwater harvesting tank (own arrangement, calculations with Cropwat, data base Savva and Frenken 2002a).

For each of the 8 crop scenarios net irrigation requirement was calculated under the present and the three future climate scenarios was calculated. By multiplying the net irrigation requirement with the drip irrigation efficiency of 75%, the gross irrigation requirement was obtained. Exemplary, the monthly gross irrigation requirement for 1 m², corresponding to the precipitation deficit, is shown in Figure 39 for the A1 subsistence scenario with one planting season, under the present climate and the three future climate scenarios. These have been computed for all the crop scenarios and can be found in the appendix.



A1 present case

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. watermelon	70.3	134.3	86.1									
2. cucumber	72.9	115.7	163.5	78.7								
3. cabbage	90.4	84.8	147.9	195.6	166.8	56.1						
4. peppers	68.9	104.9	172.0	183.1								
5. tomato	69.1	109.9	192.9	213.5	161.5	13.6						
6. patato	46.9	118.8	192.0	138.9								
7. orange	90.4	77.3	105.6	126.9	107.9	80.4	108.4	127.5	149.2	184.3	183.2	211.3

A1 future best climate scenario

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. watermelon	73.7	139.1	91.9									
2. cucumber	77.1	124.4	174.4	84.8								
3. cabbage	94.5	89.1	156.5	206.8	176.1	58.7						
4. peppers	72.7	113.7	185.9	196.4								
5. tomato	72.8	118.3	207.6	227.3	171.2	14.4						
6. patato	50.0	127.7	204.9	149.7								
7. orange	94.5	80.8	109.5	130.4	110.5	82.5	111.3	130.7	151.7	174.1	172.4	194.9

A1 future medium climate scenario

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. watermelon	76.0	142.3	95.2									
2. cucumber	79.9	129.2	180.8	86.7								
3. cabbage	97.5	90.8	155.1	202.7	172.3	57.1						
4. peppers	75.2	117.7	192.3	199.1								
5. tomato	75.2	120.0	209.9	229.6	169.6	13.7						
6. patato	52.3	132.7	212.5	152.1								
7. orange	97.5	83.3	111.3	130.1	108.3	80.3	108.3	126.8	149.3	194.4	196.9	222.0

A1 future worst climate scenario

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. watermelon	79.5	146.7	97.2									
2. cucumber	82.9	131.5	184.0	88.9								
3. cabbage	101.1	94.9	165.5	216.7	183.7	61.2						
4. peppers	78.4	120.5	196.0	205.7								
5. tomato	78.5	125.2	218.8	238.1	178.5	14.9						
6. patato	54.9	134.9	216.0	156.9								
7. orange	101.1	86.4	116.1	136.7	115.1	86.0	115.6	134.8	156.3	179.6	178.5	201.3

Figure 39: Gross irrigation requirement per month per m² (Precipitation deficit) [mm/month* m²] and efficiency of drip irrigation (0.75) with present and future climate scenarios, exemplary A1 subsistence cropping scheme (own arrangement, calculations with Cropwat, crop data: Savva and Frenken 2002a, climate data: Namibian Weather Bureau)

5.2 Analysis of the ecologic, economic and social implications

5.2.1 Ecologic analysis

5.2.1.1 Estimated impact of climate change on rainwater harvesting

For the South African Sub Region (Figure 16) annual temperatures until 2050 are projected to rise by 1.3 to 3.2°C, the median being +2.3°C. This is especially pronounced during the autumn months from September through November with +1.4 to +3.3°C (Table 8). The month with the highest temperature increase coincide with those having the highest decrease in precipitation. Calculations indicate that by 2050 annual precipitation will especially decrease in the dry season from June to August by -29% to -2%. Also from September through November precipitation is projected to decrease by -29% to moderately increase by 2% (Table 9) (IPCC 2007). During the month with the greatest amount of precipitation in northern Namibia, December through February, the corridor lays between -4% to +7% change, the median of models indicating no change. However, also during the autumn months with considerable rainfall, March and April, the model with the minimum precipitation response projects a considerable decrease by -17%, while the maximum estimation is an increase by +8%.

Table 8: Temperature Response [°C] until 2050 for A1B scenario, reduced 3:2 (data base from IPCC 2007: 854)

	Min	Median	Max
DJF	1.2	2.1	3.1
MAM	1.1	2.1	3.1
JJA	1.3	2.3	3.2
SON	1.4	2.5	3.3
Annual	1.3	2.3	3.2

Table 9: Precipitation Response [%] until 2050 for A1B scenario, reduced 3:2 (data base from IPCC 2007: 854)

	Min	Median	Max
DJF	-4	0	7
MAM	-17	0	8
JJA	-29	-15.3	-2
SON	-29	-8.7	2
Annual	-8	-2.7	4

Temperature changes effect potential evapotranspiration and therefore crop water requirements. Higher temperatures mean higher potential evapotranspiration rates and an increase in crop water requirements. Depending on which degree of temperature response will actually occur, this will be more or less pronounced.

Precipitation changes effect on gardening in two ways. Firstly, precipitation changes mean a change in the amount of rainwater that can be harvested, and the quantity of water available for irrigation in the tank. Secondly, it affects the degree of crop water requirement that is directly satisfied by rainfall. On the one hand, this means that decreasing precipitation will diminish available harvested rainwater as well as increase the proportion of crop water requirement needed from irrigation. On the other hand, increasing precipitation would signify increased harvested rainwater available for irrigation and a lower proportion of crop water requirement that needs to be satisfied by irrigation.

The predicted increase in extreme rainfall events will mean that more rain falls in fewer days. As long as the tank is not full, this will have no consequence on rainwater harvesting. However, if more rainwater comes at once, without having the possibility to withdraw water, the tank is more likely to spill over. Extreme rainfall events also mean that more rain falls on the field at once and the proportion of runoff increases while infiltration and crop uptake decreases. In this case more water would be needed from irrigation. In addition, extreme precipitation events and floods raise the risk of crop failure.

The projected substantial decrease in precipitation during the dry summer months of June to September, is practically not going to have an effect, since already now, even at low probability levels of 10 to 25%, precipitation is equal to 0 mm. The highest effect is expected to occur during October and November, as well as during the growth season in March and April, in case precipitation decreases as predicted by 50% of the models considered by the IPCC. In turn, as the other 50% predict an increase, this might have beneficial effect, lowering crop water requirements during the growth season. Table 10 summarizes calculations of this study for projected annual and seasonal precipitation amounts that occur with a probability of 75% exceedance.

Table 10: 75% dependable rainfall, for the period 1950 to 2008 and the 3 climate scenarios until 2050 (own calculations with Excel, data base: IPCC 2007 and Namibian Weather Bureau)

	1950-2008	best case 2050	medium case 2050	worst case 2050
January	60.4	64.4	60.4	58.0
February	49.5	52.7	49.5	47.5
March	31.0	33.4	31.0	25.8
April	6.2	6.6	6.2	5.1
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0.8	0.8	0.7	0.6
November	19.7	20.1	18.0	14.1
December	11.6	12.4	11.6	11.2
annual	334	347	325	307

Under the worst case, bulk precipitation decrease in absolute amounts will occur in March and November, accounting together for 10.8 mm or 40% of decrease in 3 out of 4 years. Under the best case, highest precipitation increase in absolute terms is projected for the growth period January and February (7.2 mm or 55% of increase). Under the medium case, seasonal precipitation will remain nearly unchanged, with the exception of a slight absolute decrease in November (1.7 mm). Due to changes in temperature, monthly reference crop evapotranspiration will change as shown in Table 11, being the highest in the worst case scenario and the lowest in the best case scenario. Even in the lowest best case scenario, reference crop evapotranspiration will augment by 50 mm/

year. Highest augmentations in absolute terms are to be expected for all three future scenarios for the month of October through December, were Et_0 is already now the highest throughout the year. The results calculated for Et_0 under present climate were similar to data found in the literature as previously presented in Figure 29.

Table 11: Reference crop evapotranspiration ET_0 for 1950 to 2008 and the three climate scenarios, computed with Cropwat (mm/day)

	1950-2008	best case 2050	medium case 2050	worst case 2050
January	5.61	5.75	5.85	5.98
February	5.26	5.39	5.49	5.60
March	5.02	5.16	5.27	5.40
April	4.99	5.12	5.24	5.37
May	3.88	3.98	4.06	4.15
June	2.96	3.03	3.10	3.16
July	3.98	4.09	4.18	4.27
August	4.57	4.68	4.77	4.85
September	5.62	5.76	5.86	5.95
October	6.15	6.32	6.44	6.54
November	7.34	7.54	7.69	7.81
December	7.66	7.84	7.96	8.11
annual average	5.25	5.39	5.49	5.60
annual total [mm]	1,891	1,940	1,977	2,016

5.2.1.2 Estimated impact of rainwater harvesting on the environment and the Cuvelai-Etosha Basin

In Namibia due to the climatic circumstances, 83% of precipitation evaporates immediately from the soil and is lost to the atmosphere, which is mainly due to the sparse vegetation cover and the relatively large areas exposed to the sun, heat and wind. Only 15% infiltrate into the soil, of which 14% are consumed from vegetation through evapotranspiration. Only 2% of precipitation becomes surface runoff and 1% groundwater (Figure 40) (Heyns 1995: 470).

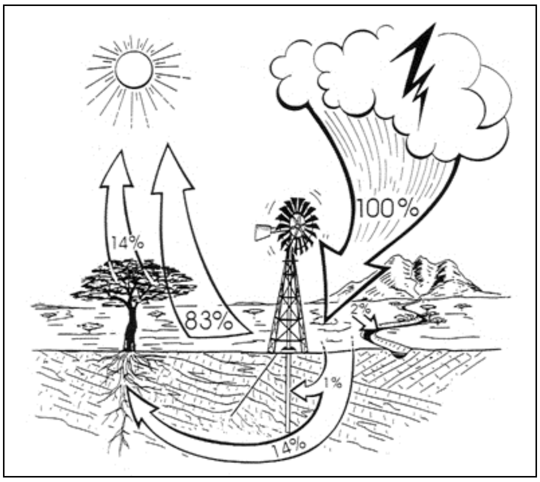


Figure 40: Water cycle in Namibia (Groundwater in Namibia 2001, in Becker and Peischl, w.y.: 3)

Due to lack of relevant data, the size of the Cuvelai- Etosha Basin can only be estimated. Its size roughly equals the size of the four regions of northern Namibia; Oshana, Omusati, Oshikoto and Ohangwena (see Figure 15), also incorporating parts of the Etosha pan. Since the Etosha pan is hardly populated, this can be neglected and considered as basin area. Moreover in abundant rainy seasons the Cuvelai drains into the Etosha Pan. The area of the four northern regions is 84,672 km², and therefore roughly the basin size. At the last population census 2001 the population living in the basin was 780,149 inhabitants and the number of households was 132,136. Each household is assumed to have a roof size of around 70 m² to 100 m², when all houses or huts are connected. If dividing the roof size of households practicing rainwater harvesting with the total basin area, it can be estimated how much rain is at first subtracted to the environment and used for irrigation requirements. If different degrees of adoption of rainwater harvesting among the households in the Cuvelai-Etosha Basin are assumed, different catchments sizes for rainwater harvesting result. The results of the estimation are given in Table 12. With a catchment area of 100 m², if 10% of the households in the Cuvelai-Etosha Basin practice rainwater harvesting, the basin area under rainwater harvesting catchment will be 0.0016%. If half of the households practice roof rainwater harvesting, 0.0078% of the basin will be converted in catchment and if presumably all households practice rainwater harvesting as much as 0.0156% of the basin will be under rainwater harvesting catchment. With an average roof catchment size of 70 m² and a 10% adoption rate of rainwater harvesting, 0.0011% of the basin area will be under catchment, ranging to a maximum of 0.0109% if all households practice rainwater harvesting.

Table 12: Estimation of the basin wide catchment size for rainwater harvesting based on different degrees of adoption

	Percentage of basin area used as RWH catchment	
Percentage of households in the basin practicing RWH	With mean household roof size 100 m²	With mean household roof size 70 m²
10%	0.0016%	0.0011%
20%	0.0031%	0.0022%
30%	0.0047%	0.0033%
40%	0.0062%	0.0044%
50%	0.0078%	0.0055%
100%	0.0156%	0.0109%

This percentage of harvested rainfall is at first subtracted to the environment. If the water is used for domestic purposes, it is returned to the water cycle at some later point. If the water is used for crop irrigation a proportion of the water is consumed by the crop through evapotranspiration. Some other proportion might infiltrate into the soil and contribute to soil moisture or groundwater recharge, however this amount is limited and the exact quantity difficult to estimate. Downstream implications may occur as less water might be available. However impacts are very difficult to foresee. Estimations over the amount of rainfall harvested basin wide are very difficult, due to the different gradient of rainfall over the basin (see also Figure 10). In addition data over the exact location of households in the basin are missing.

5.2.1.3 Ecologic benefits and disadvantages of rainwater harvesting

Rainwater harvesting is a way of increasing local provisioning capacity of water for ecosystems. Being an integral part of ecosystem functioning, availability and quality of water determines ecosystem health and productivity, both for agricultural and natural systems (Barron et al. 2009a: v, ix). Other important roles of water are erosion control, climatic control, pest and disease control through habitat regulation, water quality control and control of natural hazards (Barron 2009b: 5). Rainwater harvesting effects the landscape water balance and water flows by altering the partitioning of incoming rainfall at the local field scale affecting the amount of water that infiltrates into the soil and the amount that is diverted as surface runoff (Barron 2009b: 6). Short term advantages, based on a single rainfall event, are increased infiltration and storage of water in the soil, as flows of water are slowed. This reduces soil erosion, minimizes incidence of flooding and reduces storm water flow, limiting damage to the landscape and built structures, locally and downstream (Barron 2009c: 63, Barron 2009b: 6f). Longer term advantages, on the scale of days to months, are slower flows of water within the landscape. Longer residence times enable water to be accessed during dry periods, and used for productive purposes, including human consumption, livestock watering and increased crop and vegetation growth. It is shown in Figure 41, that rainwater harvesting causes decreases in runoff compared with the runoff from natural vegetation and majorly impacts on low flows, depending on the adoption rate of rainwater harvesting (Barron et al. 2009a: x).

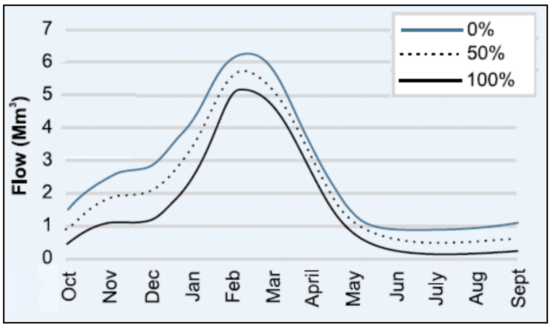


Figure 41: Potential impacts on stream flow of ex situ rainwater harvesting in two watersheds in South Africa, depending on rainwater harvesting adoption rate (0, 50 and 100%) (J. Mwenge Kahinda et al. 2008, in Barron et al. 2009: 8, changed)

However, carried out at large scale, so called negative externalities need to be considered for sustainable watershed and basin management. In this case the negative externality would be the effects of rainwater harvesting on downstream surface and ground water (Cortesi and Dyhr-Nielsen 2009: 15). Nevertheless, due to the limited amount of studies in this field, it is uncertain whether impacts might be rather negative or positive. If rain water is abstracted for additional consumptive use by crops, it is no longer available downstream. However although forest and trees ‘consume’ rainfall, they also safe-guard and generate many ecosystem services for livelihoods and economic goods (Barron 2009a: ix). In addition, substantial amounts of surface runoff may be lost during its journey through the catchment through evaporation, before reaching a stable surface or sub-surface freshwater resource (Rockström 2002: 957). Increasing the residence time of runoff flow in a watershed may have positive environmental as well as hydrological implications downstream (Rockström 2002: 956).

Rainwater harvesting reduces pressure on ecosystem services by providing additional water supply and reducing demand on surrounding surface and groundwater resources, which will be increasingly exacerbated by climate change. Consequently water over-extraction in the landscape and land degradation are reduced and more water for ecosystems is available (Sharma et al. 2009: 29, König et al. 2009: 52, Barron 2009c: 63). In Central Northern Namibia, due to the absence of rivers, this particularly concerns the *oshanas* during and after the rainy season. Improved rainfall infiltration recharges shallow groundwater sources and springs. On a large scale it might contribute to the regeneration of landscapes by increasing biomass for food, fodder, fiber and wood for human consumption. Rainwater harvesting can help communities adapt to droughts and declining availability of drinking water. (Calfoforo et al. 2009: 58). However it should be paid attention to the need of purification of the water.

Farms are the most important ecosystems for human welfare and many rural smallholder (semi-) subsistence farming systems, have high incidence of poverty and limited opportunities to cope with ecosystem changes. Variable rainfall result in poor crop water availability, reducing rain fed yields to 25 to 50% of potential yields in sub-Sahara Africa. The low agricultural productivity often offsets a negative spiral in landscape productivity, with degradation of ecosystem services through soil erosion, reduced vegetation cover, and species decline (Barron et al. 2009a: ix). Improved water provisioning through irrigation of crops with harvested rainwater in rainfed agriculture enhances local food security. Crop yields increase significantly especially due to the second crop planted during the dry period, made possible through water storage. This is beneficial for household food supply and income (Li 2000: 481 f, Sharma et al. 2009: 25)

The increased storage of water often enables in particular women to increase small-scale gardening activities. Planting of higher value crops has had an impact upon the amount of food available for domestic consumption (Joshi et al., 2005, in Cortesi and Dyhr-Nielsen 2009: 17). Also large commercial production facilities where able to mitigate the impacts of devastating dry spells with supplemental irrigation and meeting livestock water needs. Increased fodder for livestock and poultry, timber production (Sharma et al. 2009: 27, 31) reduces pressure on forests, grazing lands, wetlands and other fragile ecosystems. This helps to improve biodiversity (Sharma et al. 2009: 26), through the improvement of productive habitats, increasing species diversity amongst flora and fauna (Barron 2009b: 4, Barron 2009c: 63, Calforo et al. 2009: 58). Farmers' investment decisions are strongly influenced by their risk perceptions. All evidence suggests that if only crop water access is secured investments in soil fertility, crop, and timing of operations, will pay-off in terms of substantially increased soil and water productivity (Rockström 2002: 958).

In addition, rainwater harvesting can reduce energy requirements and carbon dioxide emissions, compared to conventional water supply technologies (Barron 2009c: 63), due to reduced pumping in the plants. (König et al. 2009: 49, 50, Calforo 2009: 57). At a broader level, because the decentralized system harvests rainwater on site before it becomes dirty, it reduces the energy required for water treatment and transportation and therefore decreases the carbon dioxide production and the long-term social cost (König et al. 2009: 51).

Finally, rainwater harvesting also affects cultural functions of ecosystem services as increased access to water in communities or households enhances the ability to carry out religious or spiritual rituals. It can also increase the aesthetic use of water. At the landscape scale, water features are often protected and given specific values by local communities by enhancing vegetation (Barron 2009b: 5).

5.2.2 Economic cost- benefit analysis

Costs

In order to undertake a cost-benefit analysis, first costs of the rainwater harvesting and the gardening facility where looked at and summarized in Table 13. Initial investment costs for the rainwater harvesting facility include costs for tank material, gutters, pipes as well as labor costs during the construction phase. Since the construction occurred within the project frame, it should be kept in mind that materials were bought at relatively high prices due to limited time. Moreover, costs accounted for labor are tariffs per hour fixed by labor unions inn Namibia at relative high level. Tools bought, journeys of consultants, meals and the like are not accounted for, since it is assumed that these are included in the labor costs of a company offering the construction. Costs differ depending on tank material and the duration of construction. All tanks have a size of 30 m², with estimated life spans of 40 years for ferrocement and brick tanks and 25 years for plastic tanks. The cheapest tank is the ferrocement tank with initial investment costs of 31,771 N$ (3,217 €), followed by the brick 34,842 N$ (3,528 €) and last the plastic tank with 41,644 N$ (4,217 €). In addition, annual maintenance costs necessary for material (10 N$/ year) are included. Maintenance costs for labor are excluded, since it can be assumed that people will repair their own or their neighbor's tank without payment. Maintenance costs are, compared to investment costs, very low. Detailed costs are shown in Table 13.

Table 13: Costs of rainwater harvesting facility and gardening facility

RWH facility costs	Tank material	Material; tank, gutters, pipes [N$]	Labor costs for construction [N$]	**Investment costs [N$]**	Annual maintainance costs [N$]
	Ferrocement	18,571	13,200	**31,771**	10
	Brick	19,242	15,600	**34,842**	10
	Plastic	36,244	5,400	**41,644**	10

Garden costs	Fencing material [N$]	Gardening and watering tools [N$]	Shade net for greenhouse [N$]	Drip irrigation plant [N$]	Hip pump [N$]	**Investment costs [N$]**	Annual maintainance costs (seeds etc.) [N$]
	757	305	664	645	270	**2,641**	20

Overall costs	Tank material	**Investment costs [N$]**	**Maintainance costs [N$]**
	Ferrocement	**34,412**	**30**
	Brick	**37,483**	**30**
	Plastic	**44,285**	**30**

Investment costs for the gardening facility include fencing material, gardening and watering tools, a shade net, a drip irrigation plant with a hip pump. Compared to the rainwater harvesting facility these costs are relatively low with 2,641 N$ (268 €). Some annual 20 N$ are assumed to be necessary for the gardening activity, such as for seeds, new material and tools. Labor costs are not included, since tank owners will work in their gardens on own behalf and for services such as plowing village inhabitants will help each other.

Benefits

Economic benefits of the harvested rainwater exclusively used for gardening activities are the revenues of horticulture products at market prices. In case the garden produce is sold at the market, this is the revenue that can be achieved per year. Otherwise, if the produce is consumed by the household and these gardening products do not need to be bought, this is the amount of money saved per year. In order to determine the revenue of gardening products under the 8 crop scenarios developed in this study, local crop yield, local market prices and crop water requirements were analyzed. These factors were evaluated for some 20 crops; a selection of crops which were included in the crop scenarios is presented in Table 14.

Table 14: Yield, prices, crop water requirement and revenue per cubic meter of water (own calculation with Excel and Cropwat, data base Price Waterhouse Coopers 2005: 13, prices for imported horticulture products in Namibia for the period January to December 2003)

Product	local yield [kg/m²]	local price [N$/kg]	revenue/ area [N$/m²]	mean annual gross crop water requirement [m³/m²] (with 75% dependable rainfall)	revenue per m³ of water [N$/m³]
cucumber	4.0	5.47	21.88	0.559	39.14
lettuce	2.9	3.49	9.97	0.549	18.17
watermelon	5.0	1.07	5.38	0.375	14.35
pepper	1.4	6.13	8.58	0.665	12.90
potato	5.2	1.54	7.98	0.632	12.63
tomato	4.0	2.91	11.67	0.944	12.36
onion	4.9	1.15	5.61	0.518	10.83
zucchini	1.8	2.09	3.85	0.425	9.05
cauliflower	2.7	2.38	6.29	0.791	7.96
cabbage	3.1	0.96	3.01	0.937	3.22
orange	1.5	0.92	1.37	1.502	0.91
mango	0.7	2.47	1.73	2.328	0.74
avocado (*)	0.6	1.00	0.59	1.175	0.50
lemon	0.1	2.02	0.10	1.502	0.07

(*) Avocado: Data not available in Price Waterhouse Coopers (2005). Yield from FAO Stat 2010, price: conservative estimate

Revenues per cubic meter of water are calculated by multiplying yield and price of each crop and dividing by the gross irrigation requirement. Figure 42 shows that cucumbers have the highest revenue per cubic meter of water, with 39 N$/m³, followed by lettuce with 18 N$/m³, watermelon (14 N$/m³) and peppers (13 N$/m³). Fruit trees have the lowest revenue per cubic meter of water (less than 1 N$/m³), due to the relative high irrigation requirement and low yields.

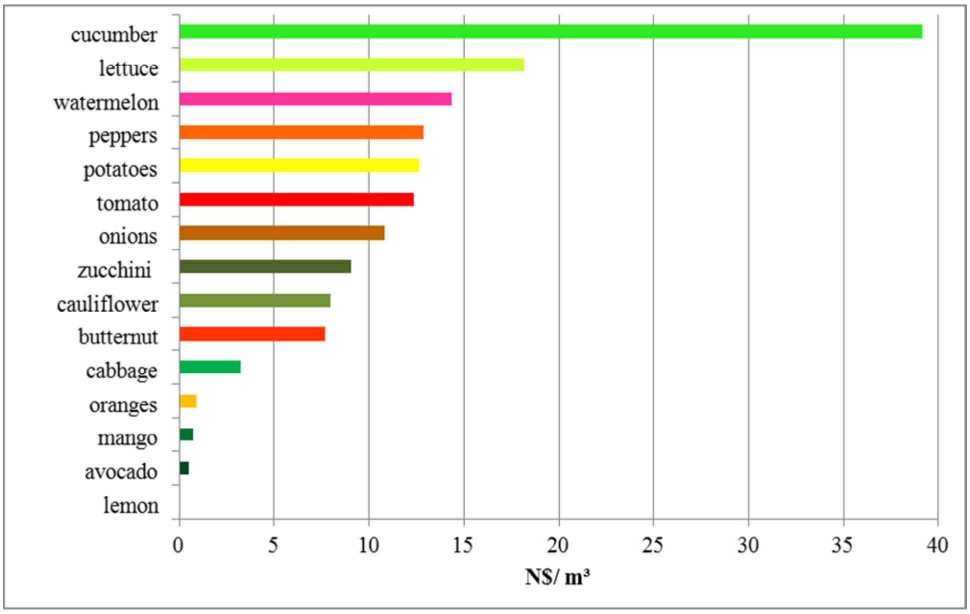


Figure 42: Revenue of crops and fruit trees per cubic meter of water [N$] (own calculation with Excel and Cropwat, data base Price Waterhouse Coopers 2005: 13)

Having this information, gross irrigation requirement, yield, revenue and field area where calculated for each crop scenario and climate scenario. The field size was verified with the tank model as described in chapter 4.2. Table 15 presents this data exemplarily for the subsistence A1 scenario and the present climate scenario. To obtain the gross irrigation requirement of the whole planted area, the gross irrigation requirement (calculated with the 75% dependable rainfall) of each crop per square meter was multiplied with the area on which each crop is grown. The sum gives the annual gross irrigation requirement of the garden. The yield was calculated by multiplying the area of each subfield with the yield of each crop, the sum of these giving the yields of all crops grown per year. Multiplying the yield of each crop with the market price of each crop gives the revenue per crop. Adding up the revenues for all crops and all seasons gives the overall revenue per year.

Table 15: Calculation of annual gross irrigation requirement, yield and revenue[3] per field, exemplarily for A1 crop scenario present climate

garden area [m²]	**61**

sub-field area [m²]	10

	planting date	harvesting date	yield [kg/m²]	price [N$/kg]	gross irrigation requirement [mm/m²], **75%** dependable rainfall	gross irrigation per field [mm]	yield per field [kg]	revenue per field [N$]
water melon	01-Jan	21-Mar	5.04	1.07	291	2,907	50	54
cucumber	01-Jan	15-Apr	4.00	5.47	431	4,308	40	219
cabbage	01-Jan	14-Jun	3.14	0.96	742	7,416	31	30
peppers	01-Jan	30-Apr	1.40	6.13	529	5,289	14	86
tomato	01-Jan	04-Jun	4.01	2.91	760	7,604	40	117
potatoe	01-Jan	25-Apr	5.17	1.54	497	4,967	52	80
orange	01-Jan	31-Dec	1.48	0.92	1,552	1,552	1	1
SUM					**4,801**	**34,043**	**229**	**586**

Likewise, yield and revenue were calculated for the other crop scenarios under present climate and future climate scenarios. Figure 43 summarizes the annual revenue for the 8 crop scenarios under the present and three future climate scenarios.

Results indicate the dominant impact of cropping pattern on revenues compared to the relative low influence of amount of planting seasons and climate scenarios. The subsistence garden scenario achieves the lowest benefits in economic terms (A1: 586 N$, A2: 510 N$), followed by the low water scenario. The cash garden achieves nearly double as much revenues as the subsistence garden. The highest revenues can be generated from the high risk garden (D1:1,619 N$ (166 €) and D2: 1,838 N$ (188 €)), which are even three times higher than those of the subsistence garden. One annual planting season almost exclusively achieves slightly higher revenues than the two annual season planting variation of the scenarios.

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[3] Price Waterhouse Coopers (2005) indicates a yield of 1.48 kg/m² for citruses. The FAO (FAO Water website) indicates yields of 3- 4.5 kg/m² for oranges. Using these higher yields for oranges indicated by the FAO the scenario would achieve higher yields and revenues.

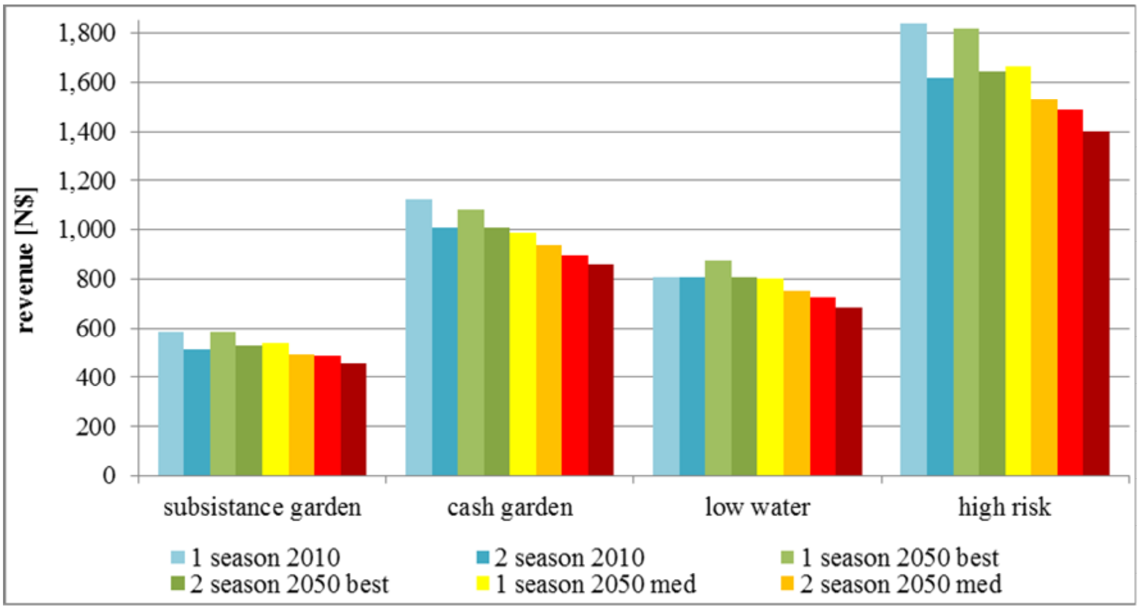


Figure 43: Annual revenue from irrigable garden area for the 8 crop scenarios under the present and the 3 future climate scenarios with 7 out of 30 years not fully irrigated

However, it is to be noted that prices are annual means, while in reality prices fluctuate, being considerably higher during the dry season than during the wet season. Therefore it can be assumed that for the second harvesting during the winter season considerably higher prices can be achieved and the two season variation of the scenario might be even more economically advantageous compared to the one season planting scenarios.

As expected, for all scenarios highest revenues can be achieved for the present and the future best climate scenario, followed by the medium and the worst future climate scenario. Compared to the present climate scenario mean revenues of crop scenarios will increase by +1% (6 N$) for the best, and decrease by -8% (87 N$) for the medium and by -15% (163 N$) for the worst climate scenario. Having smaller absolute revenues, the subsistence garden has the lowest revenue loss in the future worst case climate scenario and the high risk garden the most, having the highest absolute revenues. This revenue is calculated from a garden area, for which the rainwater harvesting tank would run dry in 7 out of 30 years and as a consequence the area could not be fully irrigated. In these years, partial crop failure will occur. Therefore, these revenues cannot be fully achieved in around 25% of years. However, as the tank runs dry additional water from the tap or the tank could be bought.

Costs-benefits

For the cost-benefit analysis two approaches have been chosen; the dynamic prime cost and static payback period. Figure 44 shows the results of the dynamic prime cost method for different tank options and crop scenarios with present climate scenario. The results indicate that all tank options under all crop scenarios have negative prime costs and are therefore not profitable. The plastic tank has the most negative prime costs, owing to its extraordinary high costs. The ferrocement is the best option, however depending on scenario its prime costs range from -4,071 N$ (-417 €) for the D1 high risk garden to -25,076 N$ (-2,569 €) for the subsistence garden.

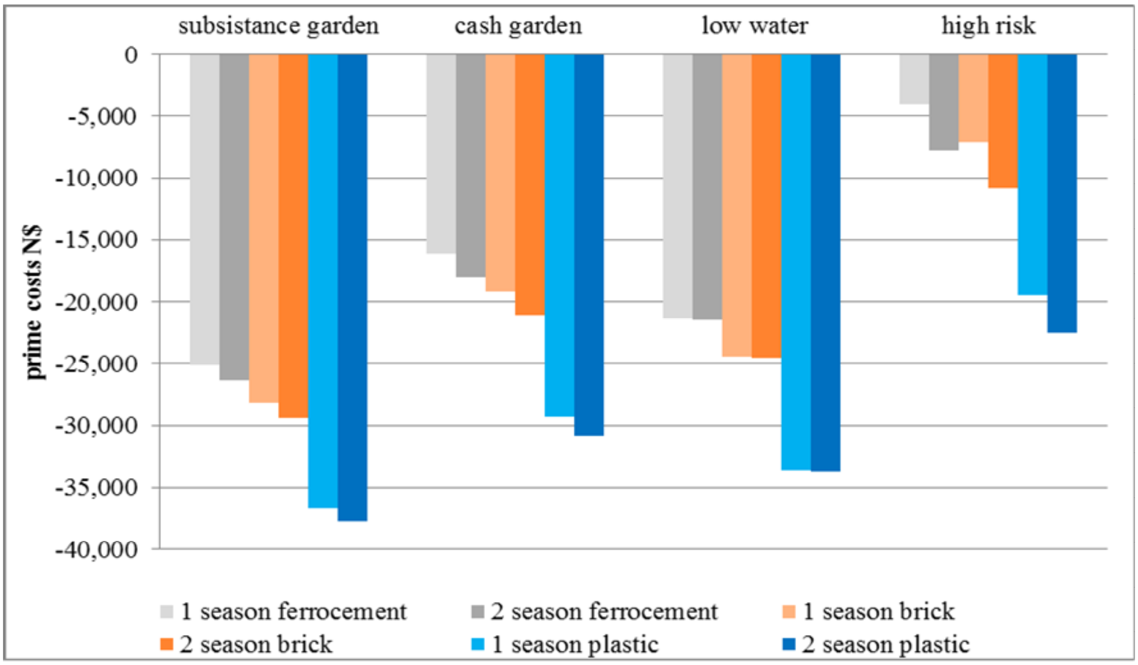


Figure 44: Dynamic prime costs [N$] of different tank options for present climate based on a cost-benefit analysis (calculations with Excel, data base: costs: Jokisch 2010, prices and yields: Price Waterhouse Coopers 2005, Irrigable area: Excel calculations, irrigation requirement: calculation with Cropwat)

In Figure 45 the same data as in Figure 44 was evaluated, but with the static payback time method. It results that profitability largely depends on the crop scenario and less on the tank material. The subsistence garden and the low water garden, as well as all scenarios with the plastic tank, are not profitable as they pay-off only after the lifespan of the tanks. The low water garden used in combination with the ferrocement tank pays-off after 44 years. The cash garden and the high-risk garden payback within the lifespan of all tanks, except for with the plastic tank, due to its shorter lifespan of only 25 years.

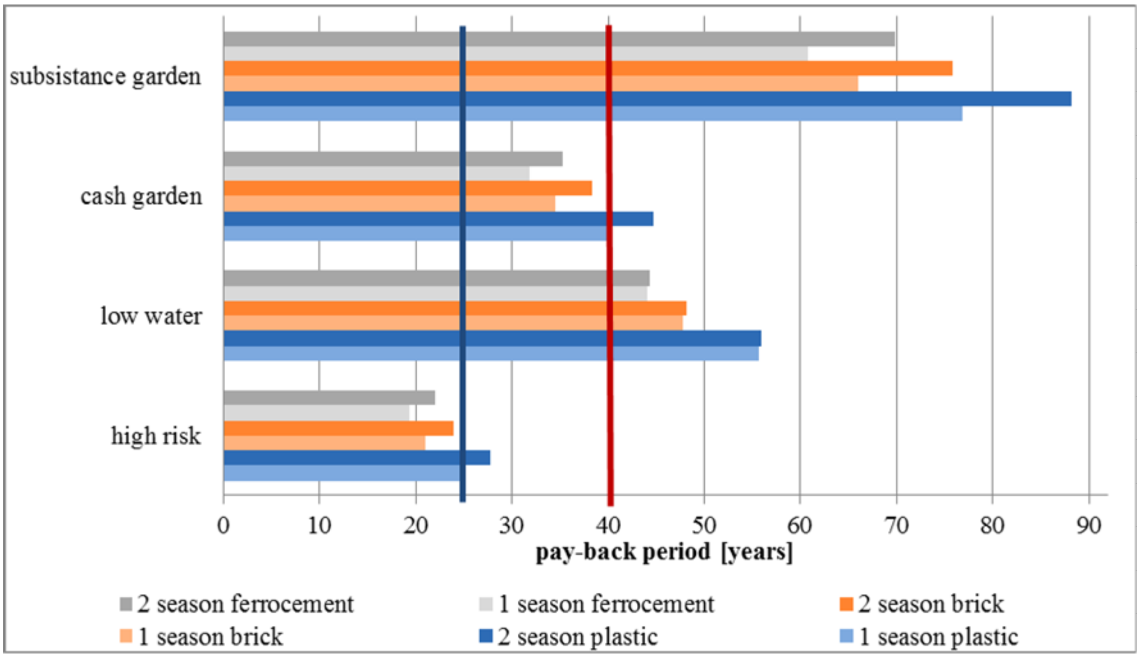


Figure 45: Static pay-back time [years] of different tank options for present climate based on a cost-benefit analysis (data base: Price Waterhouse Coopers 2005, Jokisch 2010, Savva and Frenken 2002a, Namibian Weather Bureau). Life span: plastic tank (blue line), brick and ferrocement tank (red line).

Depending on the scenario, future climate change will involve changes in precipitation, temperature and therefore crop evapotranspiration. Consequently, future revenues will differ, altering the cost-benefit analysis. For the cost-benefit analysis considering future climate change (Figure 46), only the most profitable tank, the ferrocement tank, has been evaluated for present and the future climate scenarios. The result is that profitability highly depends on the respective crop scenario. Planting one or two seasons annually has little influence on profitability. Looking at the different scenarios, under the future best climate scenario net present value is the highest, while under the future worst climate scenario it is the lowest.

Comparing the different gardens, climate change will have the lowest negative impact on the subsistence garden and the highest on the high risk garden. The subsistence garden has the lowest reduction, with net present value under present climate conditions of -25,076 N$ for one planting season and -26,352 N$ for two planting seasons, that would decrease in the future to -25,076 N$ (-1%) and -26,057 N$ (-1%) for the best, by -25,861 N$ (-3%) and -26,646N$ (-0.4%) for the medium and by -26,745 N$ (-6%) and -27,579 N$ (-3%) for the worst climate scenario. The D1 high risk garden has the highest reduction in net present value; from -4,805 N$ under present climate, down to -6,274 N$ under best future climate, -7,376 N$ under future medium climate scenario and -10,313 N$ (-43%) under worst case climate scenario.

In general, one planting season has a higher net present value compared to two planting seasons. Averaged over all future climate scenarios, net present value for two planting seasons decreases moderately for the subsistence garden (-2 to -5%%), the cash garden (-2 to -5%) and the low water garden (-15 to -5%) but notably for the high risk garden

(-11% to -41%). However, the decrease is not higher under a specific scenario, as sometimes the decrease is the highest under present, future best or medium climate scenario.

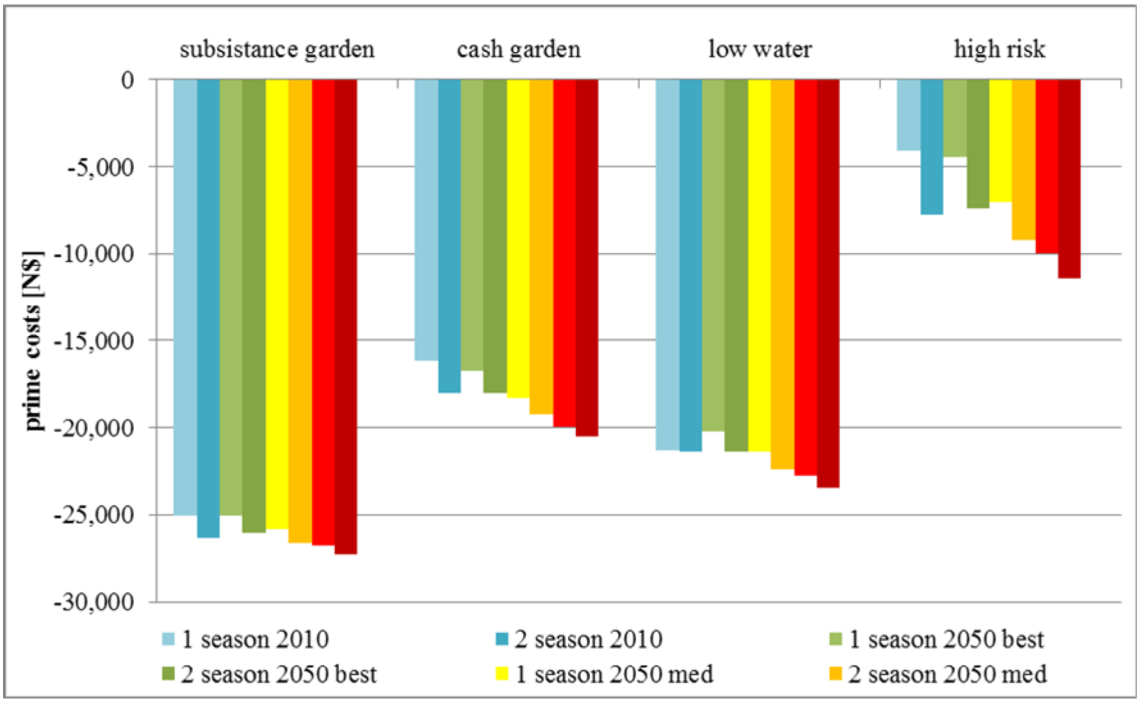


Figure 46: Dynamic prime costs [N$] under present and future climate scenarios for the ferrocement tank based on a cost-benefit analysis (own calculation, data base: Price Waterhouse Coopers 205, Jokisch 2010, Savva and Frenken 2002a, Namibian Weather Bureau, IPCC 2007)

Also the static pay-off time of the ferrocement tank under different climate scenarios (Figure 46) shows that cropping scenarios have the greater impact on profitability compared to climate scenarios (Figure 47). Usually climate scenarios do not alter the profitability, as the high risk garden pays-off in time under all climate scenarios while the subsistence and the low water garden never pay-off in time under no climate scenario. Except, the cash garden pays-off before the end of the life span under present and future best climate conditions, whereas not under future medium and worst climate conditions. Worsening future climate conditions generally cause delays in pay-off, such as by around 3 years for the D2 high risk garden and by 8 years for the B1 cash garden, comparing present climate to future worst climate conditions. The greatest delay in pay-off concerns the A1 subsistence garden, due to its lower revenues which will be considerably affected by worsening climate conditions: payback is fastest under present climate conditions and would be delayed by 24 years under the worst climate change scenario.

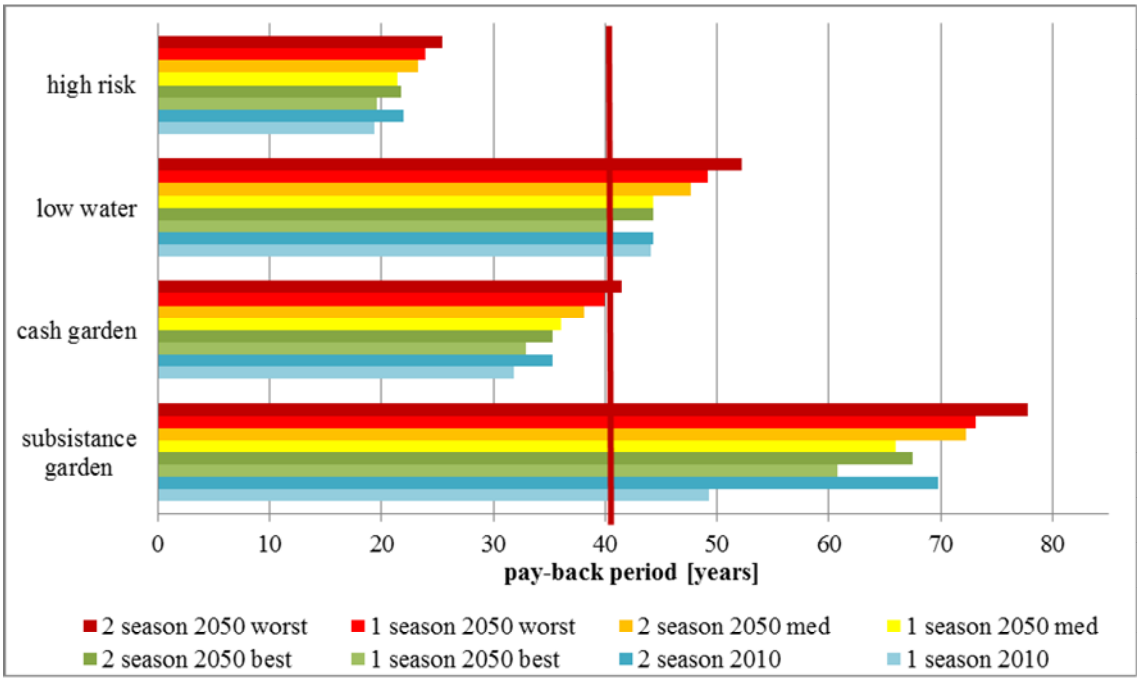


Figure 47: Static pay-back period [years] under present and future climate scenarios for the ferrocement tank based on a cost-benefit analysis (own calculation, data base: Price Waterhouse Coopers 205, Jokisch 2010, Savva and Frenken 2002a, Namibian Weather Bureau, IPCC 2007). The red line marks the end of the life span of the ferrocement tank with 40 years.

In summary, if analyzed with the dynamic prime costs method, rainwater harvesting and gardening are not at all profitable in economic terms, with no tank option, under no crop or climate scenario. However, if evaluated with the static payback time method, the cash and the high risk garden are profitable, using ferrocement or brick tank under all climate scenarios. As already mentioned, this is due to the high investment costs for the rainwater harvesting facility. As will be discussed in chapter 6, these costs are assumed to decrease if construction takes place without project conditions.

5.2.3 Social analysis

Urban gardening and the availability of horticulture products through irrigation with harvested rainwater brings numerous social benefits for individuals and the community (Swanwick 2009). However, also limitations exist, which will be briefly analyzed from workshop results (CuveWaters 2007 a-b, 2009) and existing literature. The activity of gardening brings physical and mental health improvement through increased physical activity on one side (Swanwick 2009: S66, Kingsley et al. 2009, Wakefield et al.2007). On the other side being close to nature and closely observing and taking care of plants might have spiritual and fitness benefits especially for the elderly (Kingsley et al. 2009). In addition, the availability of horticulture products improves access to food and nutrition (Wills et al. 2009: 33, Kingsley et al. 2009). Especially, it enriches the diet of consumers with important nutrients and vitamins also during the dry season, when gardening products are usually expensive and difficult to find in local markets.

Particularly vulnerable groups could benefit from this supplemental source of high value nutrition, such as pregnant women, children or people infected with diseases such as HIV or malaria who often suffer from malnutrition. If vegetable and fruits are consumed at household level, they contribute to enrich the family's diet. If sold at local markets, additional household income is earned. This can then be spent by the households, for instance for other socially valuable goods or activities such as education or paying a doctor in case of disease.

In addition, gardening activities in combination with rainwater harvesting contribute to in job creation, in an area where unemployment and underemployment is of serious concern, especially among the youth (Deffner et al. 2008: 18). Especially those unemployed or socially marginalized groups that normally would not have the chance to find a job, such as people with a HIV infection, have the opportunity to engage in a productive activity (Lux and Janowicz 2009: 38). Labor is needed for growing crops, market sale, building tanks and maintaining them, seed production and the provision of knowledge extension services for rainwater harvesting and gardening. The activity of gardening and of selling horticulture products at markets raises considerably the status and reputation of the person among the other village inhabitants and is an important source of pride (Jokisch 2010).

Moreover, the activity of gardening raises the person's own sense of worth, quality of life and spiritual feelings. It offers a possibility of increased involvement in a productive activity, come together and escape from daily pressures (Kingsley et al. 2009, Swanwick 2009: S66) and stress relief. It might be a mean to spend quality time for self and other people, increase social relationships and solidarity (Swanwick 2009: S66). It reduces social alienation and disintegration of families associated with poverty (van Averbeke 2007, Wills et al. 2009: 33) and increases trust, community cohesion and promotes social health (Wakefield et al.2007).

A study conducted by van Averbeke in South Africa, Pretoria, found that the contribution to total household income and food security was generally modest among urban garden holders. However, the livelihood benefits derived from urban farming extended far beyond material gain, reducing social alienation and the disintegration of families associated with urban poverty. Lack of space and limited access to water for irrigation were the main constraints that affected participants in urban farming (van Averbeke 2007). Equity is also an important condition for sustainability as suggested by several authors (Agarwal et al. 2001: 191, Harvey and Reed 2004: 178, Ritchie et al. 2000: 60). Also wisdom and knowledge sharing is a prerequisite for social sustainability, if also others or future generations should profit. Given the situation in northern Namibia, tenure arrangements with the community will also be very important (Ritchie et al. 2000: 62 f).

Another social benefit of rainwater harvesting, is that the water is readily available near the household and long walking distances, as in Epyeshona village of 1 to 2 km, for fetching water, can be avoided. As a result, time is saved which could be employed in other productive activities, such as gardening or market selling. Children would have more time to go to school and do their homework.

Rainwater harvesting can represent a helpful measure in climate change adaptation, as with decreasing precipitation, increase in extreme precipitation events and larger variability expected, rain can be collected and stored and used to bridge dry spells (van Steenbergen and Tuinhof 2009: 3f).

5.2.4 Criteria and indicators for sustainability

After the analysis of the ecologic, the economic and the social frame of the study, overall sustainability will be assessed through a principle and objective based top-down approach as presented earlier in chapter 4.1.3. For this a conceptual framework could be developed and according to it, relevant principles, objectives, criteria and indicators defined. The vision or principle for sustainability to which society should aspire is maintaining ecosystem integrity while assuring human well-being. A contribution to this will be the use of harvested rainwater for gardening in order to maximize yields, generate income and nutrition security while protecting water resources. Criteria in order to achieve these objectives are the efficient use of water, household income generation and securing household nutrition. These will be measured through the indicators [with corresponding measurement unit]; output/ unit of water [kg/m^3], payback time [years] and harvests/year [amount]. The more output/unit of water, the more sustainable is the environmental dimension, the more months with harvest per year, the more sustainable is the social dimension and the lower the payback time the more sustainable is the economic dimension. The proposed framework by this study is presented in Figure 48. Indicators were chosen considering the previously mentioned selection criteria in chapter 4.1.3; the indicator chosen are representative, do not encompass a too narrow field, are readily available as resulting from the previous analysis and are quantitative single values that can be clearly assigned to one dimension.

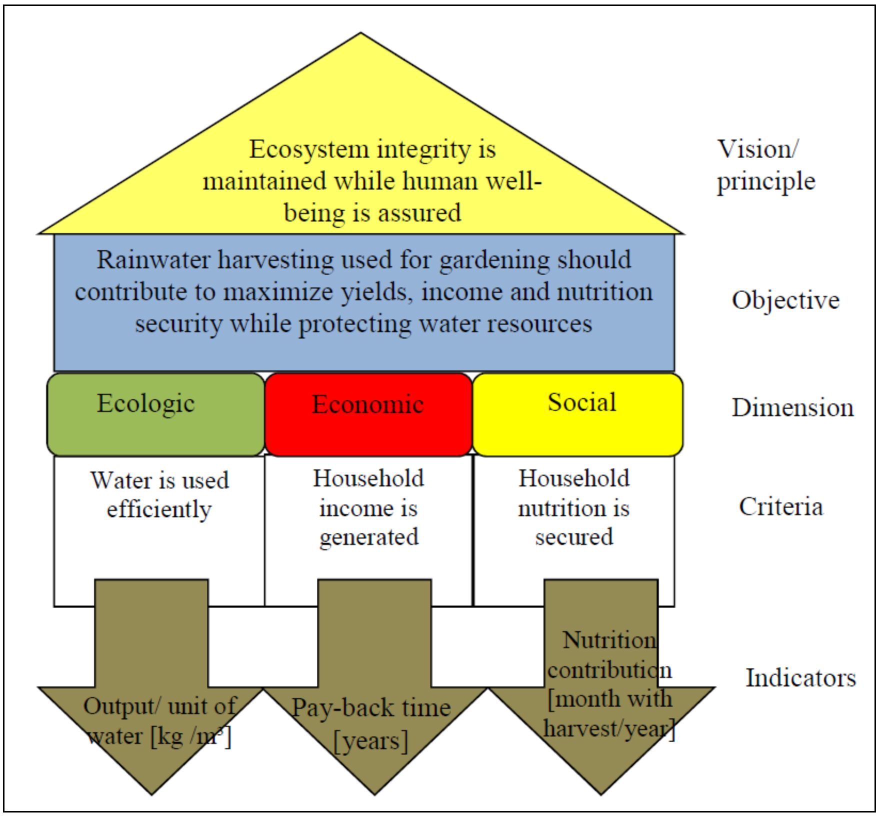


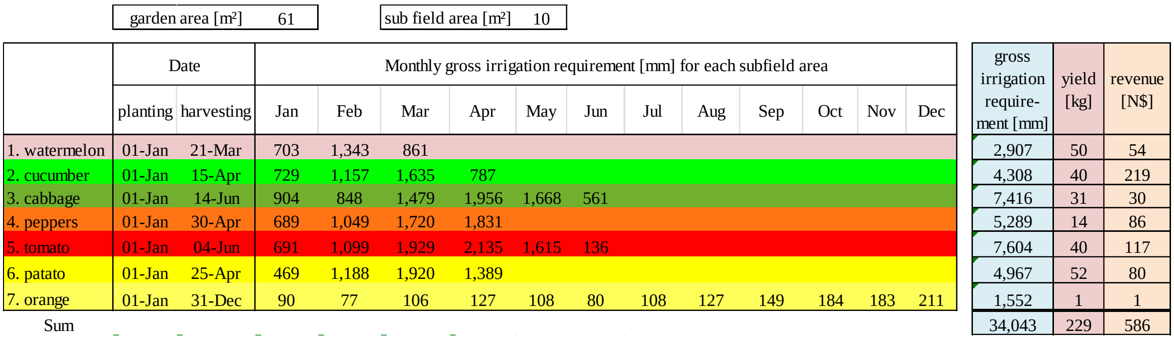
Figure 48: Principle, objective, dimensions, criteria and indicators of sustainability according to the objective based framework and the top-down or principle based approach

It is to note, that this is a reduction for the purpose of this study, in reality there are numerous other factors effecting sustainability, such as job creation, social coherence and others already discussed in the previous chapter 5.2 “Analysis of the ecologic, economic and social implications”.

5.3 Combined results of optimized water use schemes assessed for sustainability

The results of the previously developed water use schemes in chapter 5.1.3.2 “Crop water requirement”, 5.2.2 “Economic cost- benefit analysis” and 5.2.1.1 “Estimated impact of climate change on rainwater harvesting”, were combined to develop an optimal water use scheme for each crop scenario and each climate scenario. The garden area was optimized under the condition to be irrigated with a rainwater harvesting tank of 30 m³, with tank failure occurring in 25% of years due to natural variability of precipitation. As a result, the optimal garden area, the area of each sub field, the gross irrigation requirements of the overall garden area and of each subfield, as well as yields and revenues were calculated. The optimized cropping and irrigation scheme for each crop scenario under present climate conditions looks as presented in Figure 49. The other water schemes under future best, medium and worst climate conditions can be found in the appendix.

Crop scenario A1

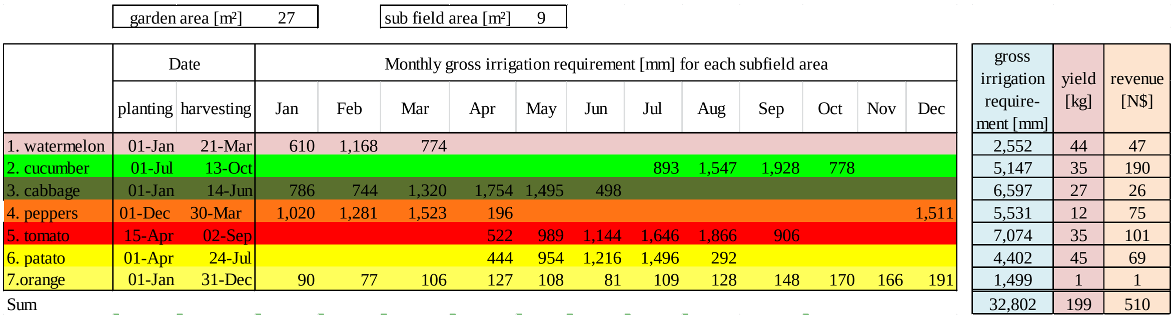


garden area [m²] 61

sub field area [m²] 10

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. watermelon	01-Jan	21-Mar	703	1,343	861										2,907	50	54
2. cucumber	01-Jan	15-Apr	729	1,157	1,635	787									4,308	40	219
3. cabbage	01-Jan	14-Jun	904	848	1,479	1,956	1,668	561							7,416	31	30
4. peppers	01-Jan	30-Apr	689	1,049	1,720	1,831									5,289	14	86
5. tomato	01-Jan	04-Jun	691	1,099	1,929	2,135	1,615	136							7,604	40	117
6. patato	01-Jan	25-Apr	469	1,188	1,920	1,389									4,967	52	80
7. orange	01-Jan	31-Dec	90	77	106	127	108	80	108	127	149	184	183	211	1,552	1	1
Sum															34,043	229	586

Crop scenario A2

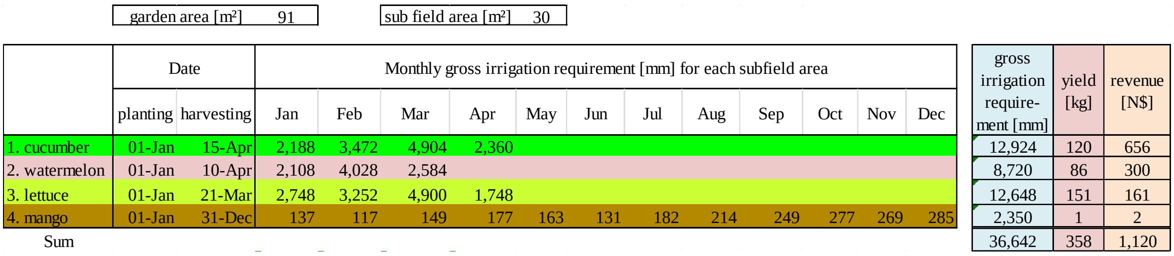


garden area [m²] 27

sub field area [m²] 9

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. watermelon	01-Jan	21-Mar	610	1,168	774										2,552	44	47
2. cucumber	01-Jul	13-Oct							893	1,547	1,928	778			5,147	35	190
3. cabbage	01-Jan	14-Jun	786	744	1,320	1,754	1,495	498							6,597	27	26
4. peppers	01-Dec	30-Mar	1,020	1,281	1,523	196								1,511	5,531	12	75
5. tomato	15-Apr	02-Sep				522	989	1,144	1,646	1,866	906				7,074	35	101
6. patato	01-Apr	24-Jul				444	954	1,216	1,496	292					4,402	45	69
7.orange	01-Jan	31-Dec	90	77	106	127	108	81	109	128	148	170	166	191	1,499	1	1
Sum															32,802	199	510

Crop scenario B1



garden area [m²] 91

sub field area [m²] 30

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. cucumber	01-Jan	15-Apr	2,188	3,472	4,904	2,360									12,924	120	656
2. watermelon	01-Jan	10-Apr	2,108	4,028	2,584										8,720	86	300
3. lettuce	01-Jan	21-Mar	2,748	3,252	4,900	1,748									12,648	151	161
4. mango	01-Jan	31-Dec	137	117	149	177	163	131	182	214	249	277	269	285	2,350	1	2
Sum															36,642	358	1,120

Crop scenario B2

garden area [m^2] 42

sub field area [m^2] 14

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. cucumber	01-Jan	15-Apr	990	1,620	2,284	1,114									6,008	54	295
2. watermelon	01-Jan	21-Mar	947	1,813	1,201										3,960	68	73
3. lettuce	01-Jan	10-Apr	1,238	1,505	2,281	821									5,845	39	135
4. cucumber	15-Apr	28-Jul				810	1,636	1,625	1,832						5,904	54	295
5. watermelon	01-May	19-Jul					1,321	1,602	1,071						3,994	68	73
6. lettuce	01-Apr	09-Jul				1,771	1,895	1,625	578						5,870	39	135
7. mango	01-Jan	31-Dec	137	117	149	177	162	131	181	213	247	272	257	264	2,307	1	2
Sum															33,888	322	1,008

Crop scenario C1

garden area [m^2] 88

sub field area [m^2] 17

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. cucumber	01-Jan	15-Apr	1,262	2,002	2,828	1,361									7,453	69	379
2. watermelon	01-Jan	21-Mar	1,216	2,323	1,490										5,029	87	93
3. lettuce	01-Jan	10-Apr	1,585	1,875	2,826	1,008									7,294	50	173
4. onion	01-Jan	05-Apr	1,612	1,859	2,816	519									6,807	84	97
5. zucchini	01-Jan	10-Apr	782	1,294	2,274	782									5,132	32	67
6. avocado	01-Jan	28-Aug	67	72	128	157	134	101	136	136					931	1	1
Sum															32,646	323	809

Crop scenario C2

garden area [m^2] 44

sub field area [m^2] 9

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. watermelon	01-Jan	21-Mar	603	1,155	765										2,523	43	46
2. onion	01-Jan	15-Apr	804	949	1,449	268									3,471	42	48
3. zucchini	01-Jan	10-Apr	390	670	1,179	411									2,649	16	33
4. cucumber	01-Jan	15-Apr	631	1,032	1,455	710									3,828	34	188
5. lettuce	01-Jan	10-Apr	789	959	1,453	523									3,723	25	86
6. watermelon	15-Apr	03-Jul				373	1,253	930	95						2,651	43	46
7. onion	01-Apr	04-Jul				1,141	1,199	1,035	167						3,543	42	48
8. zucchini	01-May	08-Aug					699	741	1,180	313					2,933	16	33
9. cucumber	15-Apr	27-Jul				516	1,042	1,035	1,167						3,761	34	188
10. lettuce	15-Apr	23-Jul				605	1,057	1,013	1,007						3,682	25	86
11. avocado	01-Jan	28-Aug	67	74	135	165	140	105	142	139					968	1	1
Sum															33,732	321	804

Crop scenario D1

garden area [m^2] 84

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. cucumber	01-Jan	15-Apr	6,126	9,722	13,731	6,608									36,187	336	1,838

Crop scenario D2

garden area [m^2] 37

sub field area [m^2] 37

	Date		Monthly gross irrigation requirement [mm] for each subfield area												gross irrigation require-ment [mm]	yield [kg]	revenue [N$]
	planting	harvesting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
1. cucumber	01-Jan	15-Apr	2,713	4,440	6,260	3,054									16,467	148	810
2. cucumber	01-May	13-Aug					3,720	4,119	6,009	2,432					16,280	148	810
Sum															32,747	296	1,619

Figure 49: Crop and irrigation schemes for crop scenarios under present climate conditions. Gross irrigation requirement calculated with drip irrigation (e=0.75) [mm/month]. Tank fails in 25% of years (7 out of 30) due to natural precipitation variability not leading to full irrigation.

The above information is also summarized in Table 16 and will be again presented in Table 17 in order to compare the present to the future climate scenarios.

Table 16: Summary of area, gross irrigation requirement, yield and revenue of 8 crop scenarios under present climate

		area [m^2]		gross irrigation requirement [m^3]		yield [kg]		revenue [N$]	
		1 season	2 seaons	1 season	2 seaons	1 season	2 seaons	1 season	2 seaons
2010	subsistance garden	61	27	34,043	32,802	229	199	586	510
	cash garden	91	42	36,642	33,888	358	322	1,120	1008
	low water	88	44	32,646	33,732	323	321	809	804
	high risk	84	37	36,187	32,747	336	296	1,838	1,619

Annual harvested rainwater from a tank of 30 m^3, with 75% dependable rainfall, can be used to irrigate a garden area of 61 m^2 to 91 m^2 depending on the crop scheme when planting one season per year, and 27 m^2 to 44 m^2 when planting two seasons per year. Due to the level of probability of rainfall accounted with, in 25% of years rainfall and therefore harvested rainwater will less, consequently calculated irrigation requirements would be sub estimated. In addition the garden area was fitted with the tank model so that the tank would fail in 25% of years. In turn, this means, that in 75% of years rainfall is likely to exceed this level of rainfall accounted with and some additional harvested rainwater might be in the tank, not needed for irrigation of the planted garden area. The subsistence garden has the lowest irrigable garden area with 61 m^2 for one planting season and 27 m^2 for two planting seasons, since its crop scheme includes crops with higher water requirements and longer growth periods. As a consequence of a smaller garden area with lower yields, but also due to a lower market value of crops planted, revenues from subsistence garden are also the lowest. However, this garden is designed for household use and the yields of each crop can well satisfy household needs. The cash garden, designed to achieve high revenues, can be irrigated on an area of 91 m^2 and 42 m^2 (one vs. two planting seasons). The low water garden, having the most water efficient crops, can be irrigated on an area of 88 m^2 vs. 44 m^2. The high risk garden, planting only water efficient cucumbers, achieves high yields and market prices and can be irrigated on an area of 84 m^2 vs. 37 m^2 (one vs. two planting seasons).

In the future, in the case of worsening climate conditions, crop water requirement is expected to rise, while precipitation is likely to decrease. On one side not as much crop water requirement can be satisfied directly with rainfall while on the other side not as much rainwater can be harvested. If the garden area under the present climate scenario is to be maintained in the future, the frequency of crop failures will augment. The degree of satisfaction of irrigation water with rainwater harvesting, under future climate scenarios, is calculated for the last 30 years with the tank model. The present climate scenario is optimized for tank failure in 7 out of 30 years. The result is presented in Figure 50 for one planting season and Figure 51 for two planting seasons.

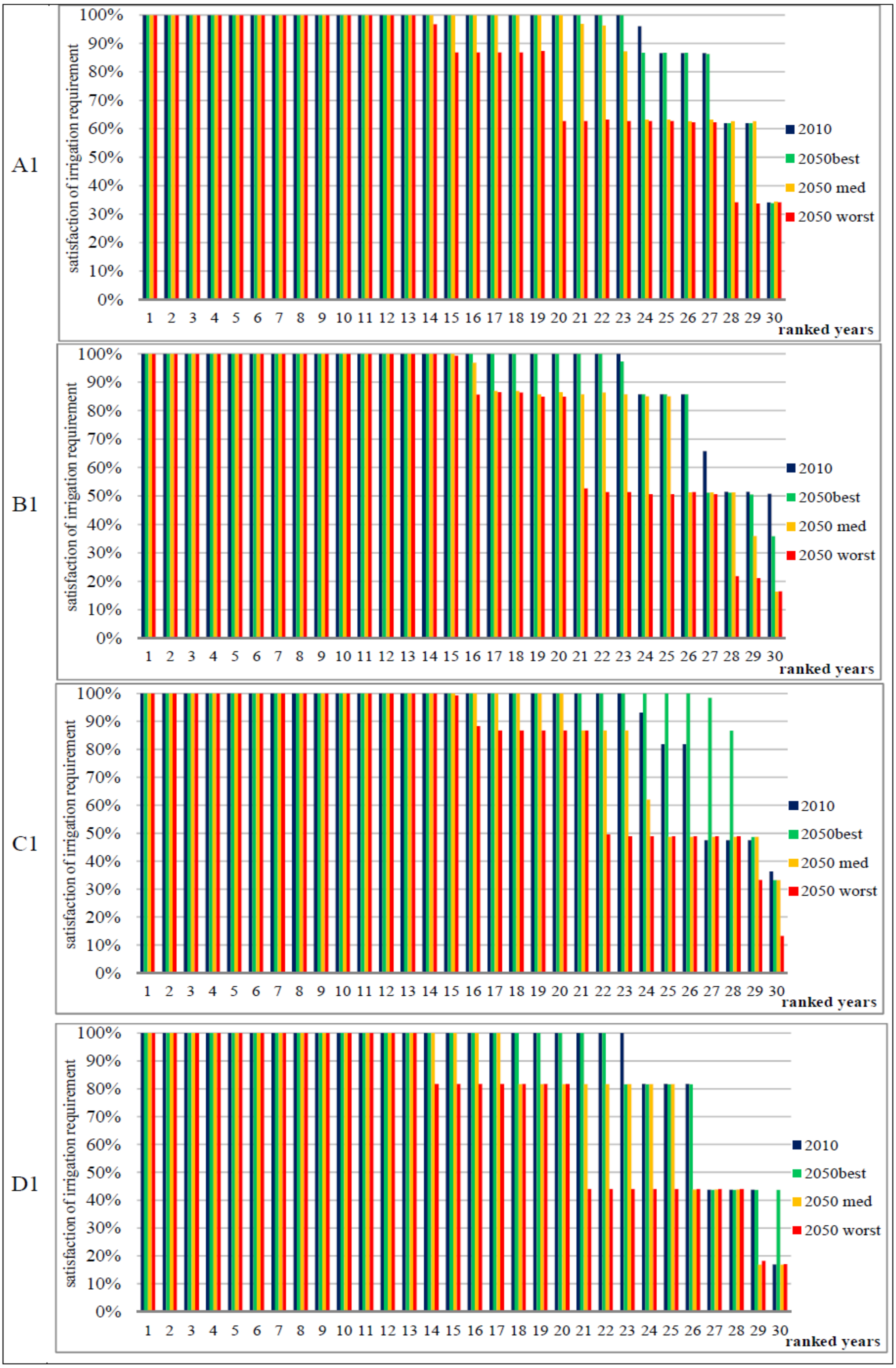


Figure 50: Degree of satisfaction of irrigation water requirement (%) per scenario for one planting season under present and 3 future climate scenarios with the gardening size as under present climate. Years are ranked, ending with the driest year.

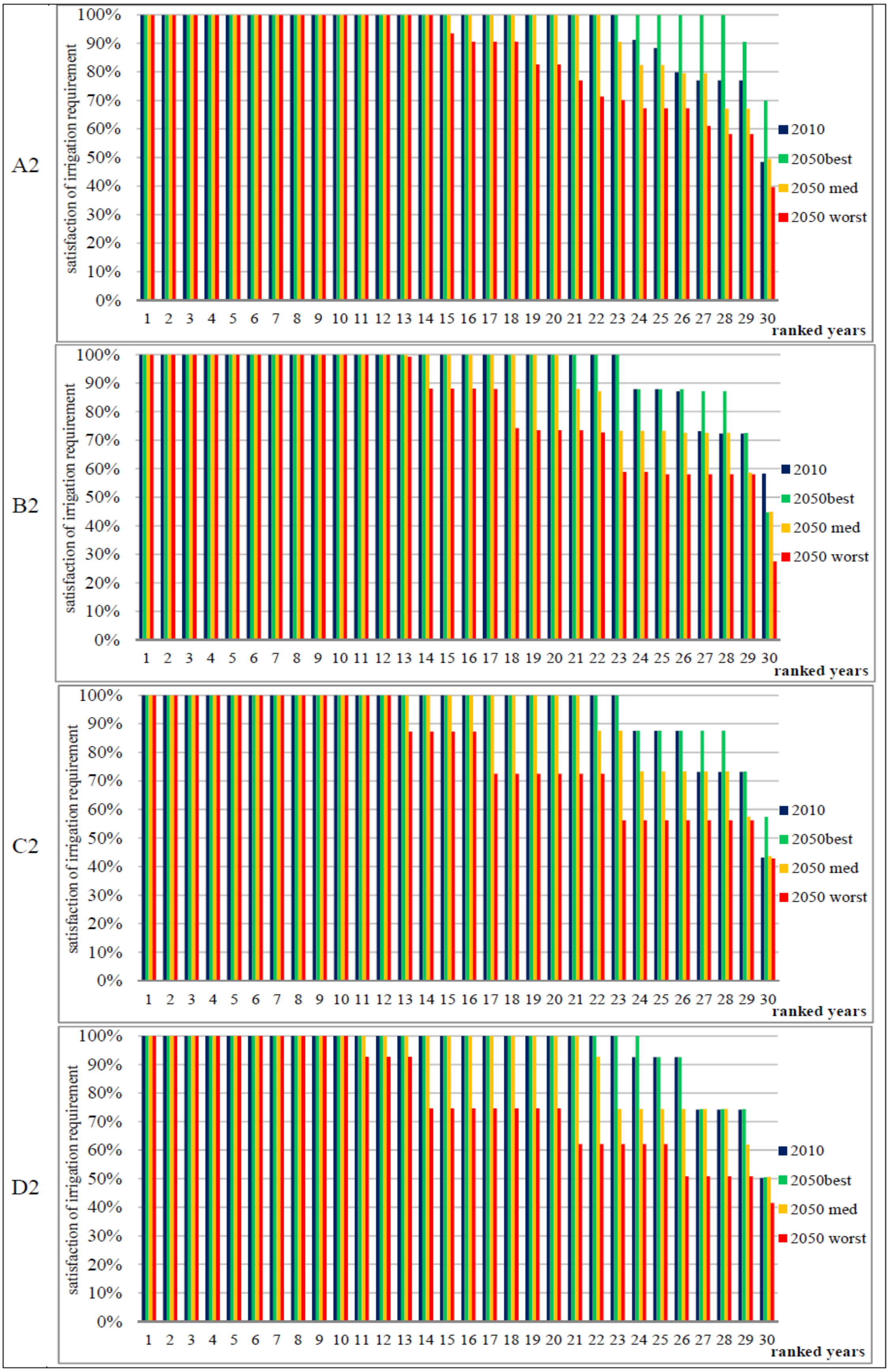


Figure 51: Degree of satisfaction of irrigation water requirement (%) per scenario for two planting seasons under present and 3 future climate scenarios with the gardening size as under present climate. Years are ranked, ending with the driest year.

As anticipated, under the future best climate scenario, tank failure will occur for the least amount of years and irrigation water requirement will be able to be met with a similar frequency as with the present climate scenario. Compared to the other scenarios, in the years when irrigation water requirement cannot be fully met, the missing quantity of water is not as excessive. Irrigation water requirement cannot be satisfied by more than 75% as under present climate conditions, in only 10% of years (3 out of 30) with one planting season and in 6% of years with two planting seasons. For the future medium climate scenario this is the case in less than 23% and 16% of years for one and two planting season, while for the worst climate scenario this is the case for even 40% and 56%. The garden with the highest degree of satisfaction of water requirement is the subsistence garden, while especially for the high risk garden and the cash garden high degrees of irrigation requirements cannot be satisfied, being often even below 50% of irrigation requirement in the worst climate scenario. In general, with two planting seasons, irrigation requirement can be satisfied in considerable more years and the quantity of missing irrigation water is not as pronounced as with only one planting season per year. Figure 52 summarizes the percentage of years in which irrigation water requirements cannot be fully covered (<100%) under different scenarios. The picture is similar as already presented above; the subsistence garden can be irrigated under future best and medium scenario nearly as under the present climate scenario. Under the worst climate scenarios all gardens cannot be irrigated in more than 50% of years, even reaching 67% of years for the D2 high risk garden.

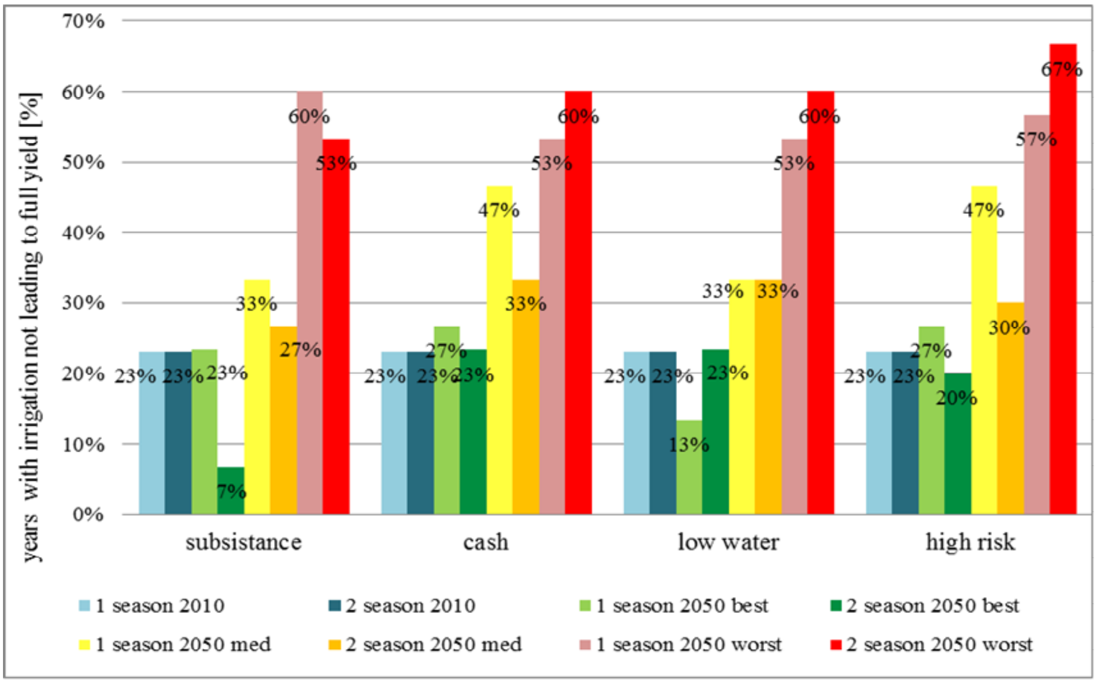


Figure 52: Comparison of crop scenarios in combination with climate scenarios concerning the percentage of years where irrigation is not sufficient to lead to full yield, on the garden size of 2010

In summary, under future climate scenarios the ability of meeting irrigation water requirements to achieve full crop yields will decrease, especially for the medium and worst climate scenario.

Sign of early warning for tank failure

Control over the quantity of water abstracted from the tank is important to optimize water use so that the supply is sufficient to for the whole crop scheme. Looking at the time series of the tank model, this study tried to determine a sign of early warning for tank failure later on in the respective year. This could serve as early warning for an adaptation measure, such as decreasing the garden area and continuing to irrigate a smaller proportion in order to save at least some crops. For this, this study tried to observe the ratio of amount of water in the tank and the amount of monthly water withdrawal from the tank. It was found that in those years in which the tank ran dry later, this ratio nearly always decreased below 2.0 or more often below 1.0 two months before that the tank was to run dry. However, in a couple of cases, the ratio of 2.0 was as well dropped even without the tank subsequently running dry. This especially occurred for one planting season and the cash, low water and high scenario garden, where the tank reached this ratio in 20 out of 30 years without running dry. In one case (D1 scenario) a higher ratio was even maintained until one month before tank failure. This sign works best for two planting seasons as well as for the subsistence and cash scenario (50% and 66% probability occurrence), and works worst for the one planting season, low water and high risk scenario (20% probability of occurrence). It can only be concluded, that the water level in the tank should be controlled, and if the ratio drops below 2.0, in around 20% to 33% of cases for one planting season and around 30 to 66% of cases for two planting seasons the tank will run dry, while in the majority of cases, roughly 67 to 80% and 70 to 34%, the water is still going to be sufficient for full irrigation.

Measures for future climate change

As an adaptation measure to projected future climate change, the gardening area should be adapted. For this, the irrigable garden area under each crop scenario was calculated again for each of the three future climate scenarios. The area was optimized for harvested rainwater with a tank of 30 m^3, with tank failure occurring in the same amount of years as under the present climate scenario, 25% of years. In these years, due to natural precipitation variability, garden areas cannot be fully irrigated using harvested rainwater. The new garden areas, irrigation requirements, yields and revenues are summarized in Figure 54 and Table 17.

When adapting the garden area to climate change, depending on crop pattern and their respective irrigation requirements, garden areas could be slightly enlarged for the best climate scenario while they would need to be considerable reduced for the medium and worst climate scenarios. Under the future best climate scenario, the garden area would need to be changed by -3 to +7 m^2 for one planting season and by 0 to +1 m^2 for two planting seasons. Under the medium scenario the garden area would need to be adapted by -1 to -16 m^2 for one planting season and by -1 to -3 m^2 for two planting seasons. Under the future worst climate scenario garden area would need to be reduced even in the range of -10 to -40 m^2 for one planting season and -3 to -7 m^2 for two planting seasons. There are no clear results which garden would require the greatest adjustments.

Table 17: Summary Table for planted area, gross irrigation requirement, yield and revenue for 2010 and 2050 best case, medium case and worst case climate scenarios. The garden area of each crop scenario is adapted to the respective climate scenario so that 6 out of 30 years cannot be fully irrigated.

		area [m²]		gross irrigation requirement [m³]		yield [kg]		revenue [N$]	
		1 season	2 seaons	1 season	2 seaons	1 season	2 seaons	1 season	2 seaons
2010	subsistance garden	61	27	34,043	32,802	229	199	586	510
	cash garden	91	42	36,642	33,888	358	322	1,120	1008
	low water	88	44	32,646	33,732	323	321	809	804
	high risk	84	37	36,187	32,747	336	296	1,838	1,619
2050 best case	subsistance garden	61	28	34,043	33,881	229	206	586	528
	cash garden	88	42	35,499	33,888	346	322	1,082	1008
	low water	95	44	35,212	33,732	349	321	874	804
	high risk	83	38	35,756	33,190	332	300	1,816	1,641
2050 medium case	subsistance garden	56	26	31,444	31,723	211	193	540	493
	cash garden	81	39	32,641	31,548	316	298	989	933
	low water	87	41	32,463	31,446	321	299	804	748
	high risk	76	35	32,741	30,977	304	280	1,663	1,532
2050 worst case	subsistance garden	51	24	28,520	29,564	190	179	487	458
	cash garden	51	36	29,669	29,209	285	275	892	859
	low water	51	38	29,346	28,779	289	273	725	683
	high risk	51	32	29,294	28,322	272	256	1,488	1,400

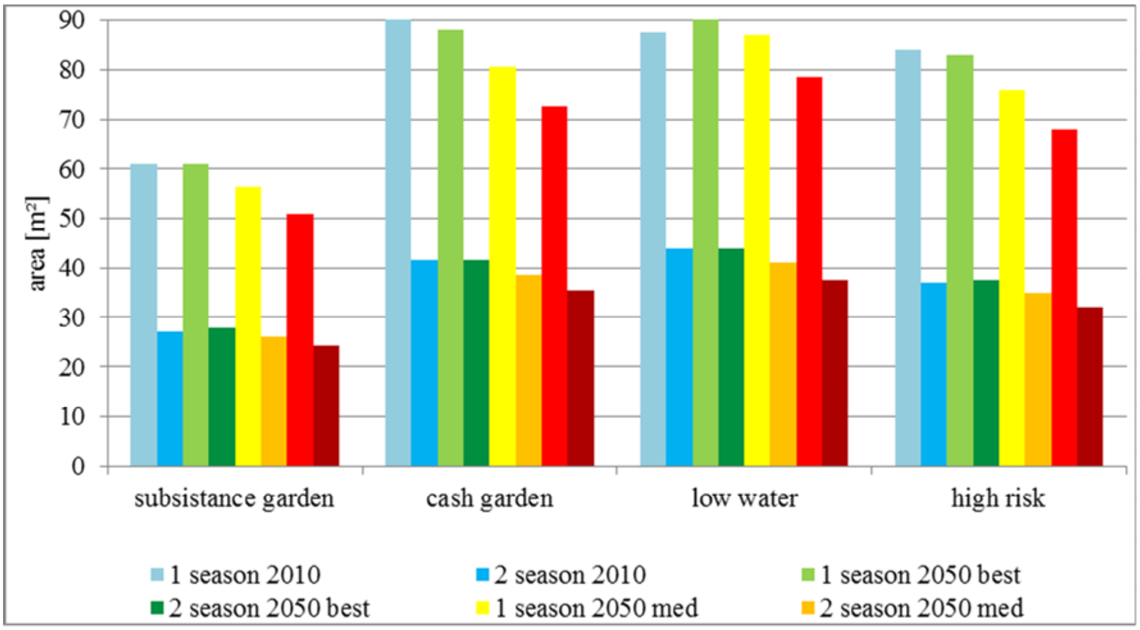


Figure 53: Annual irrigable garden area for the 8 crop scenarios under present and the 3 future climate scenarios. 7 out of 30 years cannot be fully irrigated.

For instance, the subsistence garden would need to adapt as follows; from presently planting 61 m² (1 season) and 27 m² (2 seasons), it could be slightly enlarged up to 61 m² and 38 m² under the future best climate scenario, but would need to be reduced for the medium climate scenario to 61 m² for one and to 28 m² for two planting seasons, and to 51 m² for one and 24 m² for two planting seasons under the worst climate scenario. In accordance to the garden area, also yields and revenues could slightly augment or considerably decrease. Compared the present climate to the future worst climate scenario, annual revenues could lessen as following (one vs. two planting seasons): by 99 and 53 N$ for the subsistence garden, by 227 and 149 N$ for the cash garden, by 84 and 121 N$ for the low water garden and by up to 350 and 219 N$ for the high risk garden.

As discussed earlier in chapter 2.2.2 “Frameworks of Sustainability Assessment”, the objectives-led integrated assessment approach to sustainability assessment is proactive, showing a “direction to target”, where the position of the sustainable state, the target, is unknown. Furthermore it should provide information on the “distance from target” (Pope et al. 2004: 609). This is also the case for this study as for all indicators there is no exact point or result for a sustainable or unsustainable outcome and rather the direction to the target of sustainability can be determined. Except for the economic indicator “payback period in years” a specific target for economic sustainability can be determined, which is the recovery of investment costs within the lifespan of the rainwater harvesting facility (<40 years). An increasing amount of years necessary to payback the investment costs is the “direction to target” or in other words towards economical sustainability. For payback periods longer than the lifespan, the “distance to target” can be measured by counting the years when break-even with the duration of the lifespan of 40 years would be achieved. Concerning the environmental and the social indicator, water efficiency and contribution to nutrition, there the position of the sustainable state is clearly unknown and the “direction to target” can be determined. Environmental sustainability increases if water efficiency increases and more “crop per drop”, crop output per unit of water input, can be achieved. Social sustainability increases with increasing contribution to nutrition, meaning with increasing amounts of harvests per year, so that crops can be consumed all year.

For each year, the quantity of missing water for full irrigation, the economic loss resulting from crop failures as well as additional costs to buy tap water were calculated. Results show that it would be always advantageous to buy tap water, as the costs of tap water are with 8.90 N$/m³ always below the economic loss resulting from crop failure. The only exceptions are those few cases, when the whole garden area has been fully irrigated over the whole crops’ growth period but the harvested rainwater is not sufficient to water the tree through the rest of the year. In these cases missing water is usually as low as 1.3 to 0.2 m³ and the additional purchase of tap water costs around 2 N$ to 11 N$/ year compared to the economic loss of 1 to 3 N$/year if the tree is left without water and the fruits fail. The reason for trees not being economically profitable is their relatively high water requirements, while their yield and market value of output are indicated to be low. For the long run and for non-economic reasons however it might be wiser not to let the tree dry up and rather decide to purchase tap water and spend the average extra costs of 2 N$/ year.

Sustainability of the 8 crop scenarios under present climate conditions has been assessed. The indicator scores for the 3 sustainability dimensions selected in chapter 5.2.4 “Criteria and indicators for sustainability” pay- back time, water efficiency and nutrition contribution are summarized in Table 18 and presented in Figure 54.

Table 18: Sustainability indicators and scores for rainwater harvesting and gardening of different cop scenarios with one and two planting seasons

Indicator	susbsitence		cash		low water		high risk	
	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons
pay-back time [years]	61	70	32	35	44	44	19	22
water efficiency [kg/m³]	6.7	6.1	9.8	9.5	9.9	9.5	9.3	9.0
nutritiom contribution [number of month with harvest/year]	4	6	3	4	3	5	1	2

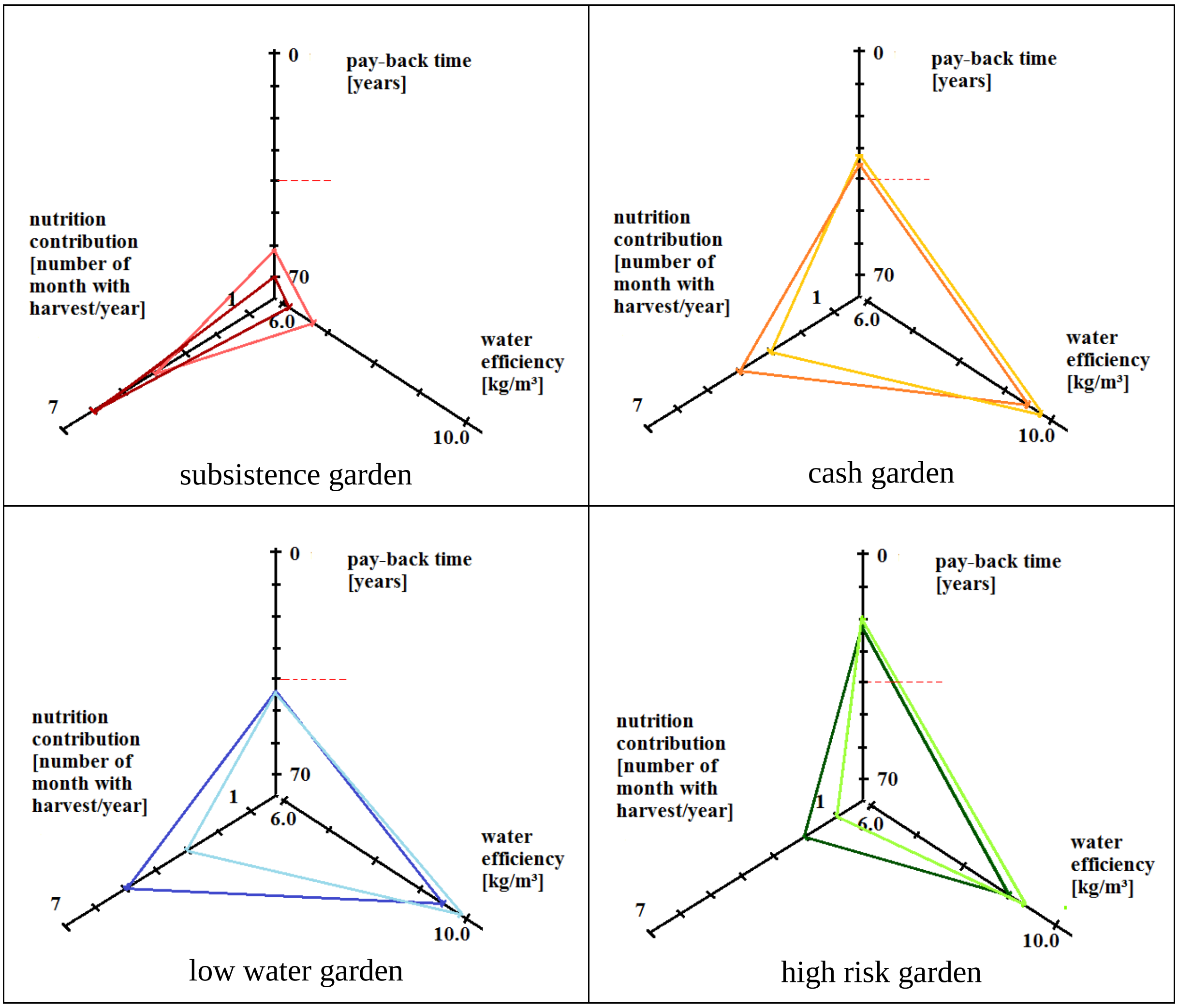


Figure 54: Sustainability indicators for rainwater harvesting and gardening of different cop scenarios with one and two planting season (from above left to down right: subsistence garden A1 (light red) and A2 (dark red), cash garden B1 (light yellow) and B2 (dark yellow), low water garden C1 (light blue) and C2 (dark blue), high risk garden D1 (light green) and D2 (dark green).

The spider web diagrams (Figure 54) give a picture of how sustainable a crop scenario is. The Sustainability Assessment is only valid for years when tank does not fail and there is full crop yield. The greater the area of a crop scenario in the diagram, the more sustainable it can be considered. However, if the economic indicator payback time is below the red dotted line, marking the lifespan of 40 years of the ferrocement tank, the crop scenario can be considered as not sustainable. The subsistence garden scenario results in the smallest overall area, where the area with two annual planting seasons is even smaller than the one with one annual planting season. Even though two annual planting seasons of the subsistence garden score better on nutrition contribution, they have very low scores for payback time and water efficiency and therefore it can be considered as not sustainable. The high risk garden scores high on payback time and water efficiency (9.3 and 9.0), but very low on nutrition contribution, with only 1 and 2 months of harvest per years. Due to the low social indicator score, it is questionable if the scenario can be considered sustainable. The most sustainable scenarios are the low water and the cash garden. The low water scenario scores the highest of all scenarios on water efficiency (9.9 and 9.5) and fairly high on nutrition contribution with 3 and 5 months of harvest per year, yet its economic payback time with 45 years does not exceed the threshold of economic sustainability, as not all investment costs can be recovered within the lifespan of the rainwater harvesting tank. The cash garden scenario scores high on water efficiency (9.8 and 9.5), fairly high on nutrition contribution (3 and 4 months of harvest) and exceeds the threshold of economic sustainability having a payback time of 32 and 35 years. Therefore the cash garden is clearly the most sustainable of the proposed scenarios, while the subsistence garden is the least sustainable, mostly due to the economic indicator.

Comparing one and two annual planting seasons, two planting seasons score, without exception, higher on nutrition contribution and lower on water efficiency. This was expected, since more planting seasons per year augment the frequency of harvest within a year and aid to nutrition contribution. However, when planting in the dry season, water efficiency decreases as irrigation water employed per unit of output increases, due to higher irrigation requirement in the dry season. On the other side, one planting season scores better on payback time. The reason for this is that planting in the rainy season gives the possibility to plant a greater area as less irrigation water is required; this gives the possibility of achieving higher yields, which can achieve higher revenues at markets. All three sustainability dimensions being equally important, it is difficult to say whether in general one or two planting seasons are more sustainable. However, differences in indicator scores for payback time and water efficiency are relatively low among one or two planting seasons within a scenario. It can be concluded that the number of planting seasons has little influence on sustainability while crop scenarios have significantly more influence on sustainability.

6 Discussion and applicability

6.1 Limits and uncertainty of the results of the study

For the cost-benefit analysis, costs for fertilizer and pesticides where not considered. The absence of sufficient fertilizer and pest control however reduces crop evapotranspiration and yield (Savva and Frenken 2002a: 4), while crop evapotranspiration was calculated under standard conditions, meaning for well-managed, well-fertilized, non-stressed crops under optimal conditions. The study assumes that since most households own animals, gardeners will use their goat and chicken excrements as fertilizer. Pesticides worth 150 N$ were purchased by the project in 2010 for a garden area of 1,350 m² (Jokisch 15.10.2010, orally), corresponding to 0.111 N$ per m². For a garden area of 60 to 90 m² as calculated by this study this would mean an extra cost of 7 N$ to10 N$ per garden and per year, which is not excessive. These costs should be added to the cost-benefit analysis. Unfortunately the data was available only shortly before the termination of this study.

Market prices for the calculation of economic benefits from gardening output are assumed, for the purpose of this study, to be constant throughout the year and over the whole lifespan of the project. Gittinger (1982) acknowledges that normally constant prices are used because of the assumption that general inflation will exert the same relative effect on both costs and benefits. It is also difficult to forecast inflation beyond about three years (in Senkondo 2004: 70). This study did not consider future market price developments of horticulture products, due to the lack of information and the high level of uncertainty that would be tied to it. It is not considered, that due to tank failures and occurring droughts in some years, crops fail and as a consequence revenues will be lower. It is also not considered that not all of the products can be sold at markets and some will deteriorate and not achieve the full price or will have to be thrown away.

In this study, due to the limited availability of climatic data of temperature and humidity of only 3 full years and of wind speed of only one full year, the calculation of reference crop evapotranspiration ET_o and as a consequence of crop water requirements might alter. Especially as discussed earlier in the study (5.1.3.2 “Crop water requirement”), the values calculated by this study for the month of June might be lower and for December higher than in reality.

6.2 (Un)Certainty of models used

For the calculation of reference crop evapotranspiration, the FAO Penmen-Monteith method is usually considered as a standard method (Trabucco et al. 2008: 84). Trabucco et al. (2008) tested five methods for the calculation of crop evapotranspiration and compared them. A major drawback of the FAO Penmen-Monteith method is its relatively high need for specific data for a variety of parameters, which are reliably observed by only a limited number of meteorological stations around the globe.

Particularly in developing countries they are often lacking or incomplete (Trabucco et al. 2008: 84). Trabucco et al. (2008) tested the Penmen-Monteith Method of the FAO and compared observed and predicted model estimates. It found a mean difference for Africa of 11.1% for January and 12.7 % for July, with standard deviations of 12.6 and 16.0 respectively. These values are relatively low, compared to other methods such as from Thornthwaite (42 and 32%) or Hargreaves (22 and 20 %). In addition, predicted model estimates for Africa are generally considerably more accurate than those for South America (with 35 and 24% difference for the Penmen-Monteith method and even more for the other two methods). (Trabucco et al. 2008: 85).

Moreover reference crop evapotranspiration, using the Penmen-Monteith Method, can be calculated manually instead of using tools such as Cropwat. Savva and Frenken (202a) compared their results from Cropwat with the manual calculation of reference crop evapotranspiration for Harare Kutsaga Research Station, Zimbabwe. They found that the results of the two methods were very close, the values of ET_o calculated with Cropwat being slightly higher, but the maximum difference resulting in their case only in 0.4 mm/day (Savva and Frenken 2002a: 21).

In addition, uncertainties are tied to the designed tank model by this study, as it assumes that the tank always functions, no water will be lost through leaks and its quality will always be suitable for gardening irrigation so that all harvested rain can be used. It assumes, tank owners will not withdraw any supplemental water for household consumption and the like. The tank model does not include tank maintenance periods during which rainwater cannot be collected.

6.3 Treatment of uncertainty

Under present circumstances, due to natural inter-annual variability, each level of annual precipitation is tied to a certain probability. In order to deal with the uncertainty of the level of precipitation in the upcoming years when calculating crop irrigation requirements, this study selects to use a level of rainfall with 75% probability of exceedance, meaning in 25% of years precipitation falls below this value. In these 25% of years the proportion of crop water requirements covered by rain will be lower and consequently irrigation requirements will be higher than calculated. Given this level of precipitation, the gardening area is designed so that the harvested rainwater in the tank is sufficient in 75% of years and not sufficient in 25% of years (rounded to 7 out of 30 years). One could argue that this probability level is fairly high. Particularly in dry years, when anyway less rainwater could be harvested, irrigation requirements are higher than foreseen. Nonetheless, it should be considered that if irrigation requirements are calculated to be sufficient in all years, even those years with precipitation with probability levels of exceedance of 100%, corresponding to an annual precipitation of merely more than 100 mm (Figure 25), a great quantity of precipitation would remain unused in other years and irrigation requirements calculated would be significantly too high. As well, if the garden area was to be designed so that harvested rainwater in the tank would be enough for 100% of years, in the majority of years an abundant quantity of rain would be unused, the garden area too small and the harvested rainwater in the tank spilling over.

As presented earlier in chapter 3.2.4 “key uncertainties”, concerning future climate change projections, temperature projection have higher levels of confidence than precipitation projections (IPCC 2007: 73). In order to deal with this uncertainty the IPCC (2007) gives a „likely range of uncertainty” which was used for this study. This can be understood as a corridor within all values are possible (temperature, precipitation and reference crop evapotranspiration). Since the study could not consider future projected change in humidity, wind speed and daily sunshine length in order to calculate reference crop evapotranspiration, due to the lack of available and certain projections, the calculations of future crop water requirements are also tied to a certain level of uncertainty and should be considered as mere indicative value.

6.4 Comparability to results of other studies

Results of this study, such as crop water requirement, water efficiency, payback period and net present value can be compared to results of other previous studies.

Crop water requirements calculated by this study were compared to indicative values given by the FAO (Critchley 1991: 2). These values differ strongly depending on climate, length of growth period and planting period (FAO Water website). As can be seen from Figure 55, all calculated results by this study are within the range indicated by the FAO, with the exception of tomatoes and cabbages for which this study has calculated higher crop water needs. This is a consequence of assuming longer growth periods (155 days) as indicated by Allen et al. (1998) and Savva and Frenken (2002a: 40) for semi-arid regions, while this FAO indicative value only assumes a growth period of 90 to 120 days. The range occurring for the values of this study are due to differing planting periods within a year as discussed earlier.

Crop	Mean crop water requirement over growth period calculated by this study (and range due to different planting dates within a year in brackets) [mm]	Crop water requirement over growth period indicated by the FAO (in Critchley, 1991) [mm]
citrus	1,127 (1,105 - 1,168)	900 - 1,200
beans	434 (338 -622)	300 -500
millet	356 (258 -504)	450 - 650
cabbage	720 (547- 907)	350- 500
onion	338 (300- 546)	350- 550
pepper	499 (407 - 694)	600- 900
tomato	708 (560- 928)	400- 600

Figure 55: Crop water requirements [mm] over growth period, results of this study compared to indicative values given by the FAO in Critchley 1991: 2.

Nantanga et al. (2007) give an indicative value for irrigation requirement northern Namibia of around 1.2 to 1.5 m^3/m^2, without specification of crop nor planting period or method of calculation. Compared to this, the results of the study are lower being around 0.4 to 0.6 m^2/m^3 (Figure 58).

Crop water efficiency, or sometimes also called crop productivity, greatly varies according to the specific conditions under which the crop is grown (FAO Land and water website). In order to have some reference the results of this study for crop water efficiency were compared to indicative values given by the FAO (Figure 56). It shows that values are more or less in the indicated range, some values are lower (cabbage, tomato, citrus) and some higher (watermelon and onion), however this might be due to differing climate conditions and the salinity of the soil which considerably effect yields. In general, it is not possible to conclude, whether this comparison means that calculated water efficiency by this study is high or low, as no comparative values for northern Namibia could be found. The indicative values of the FAO apply for all climates, while in northern Namibia the climate, with high temperatures and low precipitation is not the most favorable one.

Crop	Water efficiency [kg/m^3] mean results of this study over different crop scenarios and amount of annual planting date	Water efficiency [kg/m^3] indicated by FAO Water
cabbage	4	12 -20
potato	10	6 -11.6
tomato	5	10 -12
onion	12	8 - 10
pepper	2.4	1.5 -3
watermelon	17	5 - 8
citrus	1	2- 5

Figure 56: Water utilization efficiency for harvested yield [kg/m^3] calculated by this study and compared to literature values (FAO Water website, Pescod 1992: 5.1.2, FAO 2003: 3)

For the net present value, Senkondo et al. (2004: 77) found that in Tanzania investment in rainwater harvesting for crop production is profitable in the long run and while costs could be covered, profits can still be attained. The net present value for planting onions using harvested rainwater was positive over the lifespan of the facility with +2,583,259 Tanzanian Schilling (+1,238 €), even using a rather high discounting rate of 10%. Similar results have also been recorded by Kunze (2000) in West Africa. Unfortunately concerning the payback period of rainwater harvesting tanks no comparable values for developing, semi-arid countries could be found in the literature.

The results of this study can also be applied for other developing countries, with similar incomes and prices as well as similar semi-arid climates with similar rainy seasons and sandy soils. In addition, local conditions should imply similar village structures, lack of canalization and flat landscape.

The biggest issue for sustainability is the economic dimension, where the costs of the rainwater harvesting facility are too excessive. This is also clear, when comparing the costs of a rainwater harvesting facility in northern Namibia with those in the other regions analyzed in chapter 2.1.1 “Overview of rainwater harvesting”. In Gansu Province in China costs of a 30 m³ tank are indicated to be around 125 US$, including construction material and labor costs (Li et al. 2000: 480). In Gujarat state in India, costs of an underground tank of 20 m² for rooftop harvesting comprised 573 US$[4] in 1995 (Agarwal et al. 2001: 83 f). The calculated costs by this study for a 30 m³ ferrocement tank in northern Namibia were 4,439 US$[5] (31,771 N$) in 2010. Since the sustainability of the whole activity of rainwater harvesting and gardening depends on this, the costs need to be verified as to be discussed in the following chapter. However, for the single household this result could become irrelevant, if the rainwater harvesting facilities would be subsidized by the government, such as in Gansu Province China (see chapter 2.1.2.1).

6.5 Need of field verification of results

The results of this study need to be verified locally under real world conditions. Calculated crop water requirements need to be verified empirically. So far during the pilot phase of the project, it is reported that gardeners planted their crops around July and used an estimate 300 l/ day and per 150 m² garden area (corresponding to 60 l/ month and m²) using watering cans, while the ideal quantity suggested by a consultant in charge of the gardens would be around 100 l/ day and per 150 m² of garden area (corresponding to 20 l/ month and m²) (Jokisch 15.10.2010, orally). The result of this study for irrigation requirement, averaged over all crop scenarios for present climate and applying water with an efficiency of 75%, is very roughly 65 l/ month and m² at the initial growth staged ($K_{c\ ini}$), around 140 to 150 l/month and m² at crop development and mid-season stage ($K_{c\ mid}$) and around 40 to 90 l/month and m² for the late season stage ($K_{c\ end}$). These values do not include irrigation of trees, as this would considerably change the values and in the pilot gardens no trees were planted. In addition, irrigation strongly depends on the planting period; Net irrigation water requirements over the entire growth period of a crop are about 40 to 50% lower for a crop planted in the most favorable period (January) compared to if the same crop was planted in the most unfavorable period (mostly September).

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[4] Costs of 18,000 Rs as indicated by Agarwal et al. 2001 for 1995. With the exchange rate of 1.1.1995 this would correspond to 573 US$ (http://www.oanda.com)

[5] Exchange rate of 25.10.2010 calculated with http://www.oanda.com

As well the local costs of the rainwater harvesting facilities need to be verified without project conditions. Costs of the pilot plants where considerably high due to the building phase shortly before Christmas when prices are usually high due to higher demand before holidays. As well, construction of the tanks occurred during the rainy season when the *oshanas* were flooded and instead of being able to use its sand, expensive building materials from a do-it-yourself supermarket had to be purchased at high costs. Due to the training of tank builders, the construction phase lasted longer than if already experienced builders construct a tank, which reduces labor costs. According to project estimations (Jokisch 2010), building costs could be reduced by 10 to 25% under real conditions compared to the pilot project's costs.

Moreover the crop schemes should be verified with the local population, concerning the time of planting and harvest. Commencing with January and especially the period of May through July (Figure 57) village inhabitants are traditionally working on their pearly millet (Mahangu) fields. Even though they might be officially considered as unemployed or underemployed they might not have enough time for their gardens during this period of the year. As confirmed during project workshops (Jokisch, orally 15.10.2010), villagers would prefer to work on their gardens during the dry period (August through October) when they are not working on their fields. Unfortunately, this is indeed the most inefficient season for gardening and harvested water in the tank would hardly be sufficient. In addition, this study found that for planting 3 seasons a year the tank would not be sufficient, so that a maximum amount of 2 seasons can be planted, ideally in the period from December to July.

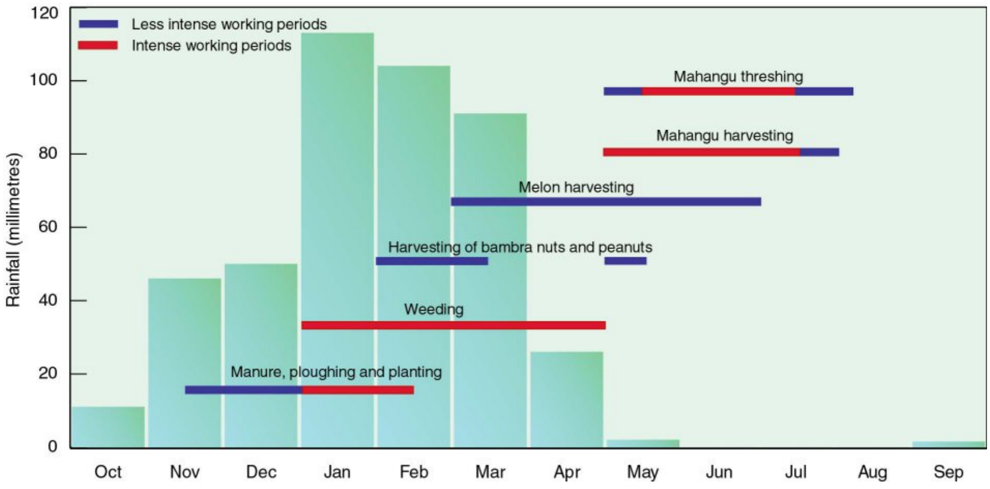

Figure 57: Farming timetable in northern Namibia (MET website)

Market prices of horticulture crops rely on an analysis of Price Waterhouse Coopers (2005) of imported horticulture products for the period January to December 2003 and are given in N$ per ton. In reality however, prices fluctuate considerably, being significantly higher during the dry season than during the rainy season.

6.6 Interrelations between sustainability dimensions and measures to raise sustainability

As stated by George (1999, 2001), Gibson (2001) and Pope (2004), a principles-based approach to Sustainability Assessment emphasizes and examines interconnections and interdependencies between the three pillars of sustainability and attempts to identify beneficial interventions and fully expose unavoidable trade-offs. In the following paragraph interdependencies of pillars will be examined and measures to raise a given indicator denominated.

To raise the environmental indicator, crops with lower water requirement should be planted and those with high water requirements not. Planting tomatoes, cabbages, peppers and potatoes should be avoided. This might however have a negative impact on the economic indicator, as these crops have high market prices and augment revenue. Also trees have high water requirements and score very low on water efficiency. Nevertheless, it is still recommended to plant one tree per garden, as besides offering shade and having esthetic values, it has numerous other environmental and social benefits. To a smaller degree, water efficiency can also be increased by planting only during the period with the lowest irrigation requirements. This will however impact on the social indicator; as a consequence the amount of months with harvest per year will be reduced.

The social indicator “number of harvests per year” is relatively easy to increase. All that has to be done is to stronger vary the planting times of crops, which will lead to more harvests per year. However, this might have a negative draw back on the environmental dimension, as water efficiency might decrease if the most water efficient planting periods throughout the year are not chosen, when irrigation requirement is the lowest. This will in turn also impact the economic indicator, as with varying planting periods and lower focus on the most water efficient planting period, harvested rainwater in the tank will only be sufficient for a smaller garden area, meaning lower yields, lower revenues and longer payback times.

Raising the economic indicator, payback time, would imply to reduce costs of the rainwater harvesting and the garden facility while increasing revenues of garden produce. In order to raise revenues, those crops with the more advantageous yield and price per kg, such as cucumber, tomatoes, watermelon and peppers should preferably be planted. This however, will have a negative impact on the environmental indicator, as some of these crops have low water efficiencies. In addition, revenues can be raised, if the quantities of different crops planted are reduced, planting only few crops with high market returns. This however, might have a negative consequence on the social indicator, especially if crops are to be used for subsistence. Of course, also costs can be reduced, which is probably difficult to achieve below a minimum cost-level.

For the local population and single households, the economic indicator payback time might be the most determining one, for their investment decision for a rainwater harvesting facility and the engagement in the activity of gardening. Most probably, a private household will not engage in such an activity, if the economic side is not sustainable, although it might have social advantages, while environmental advantages might be perceived as not so important. Nonetheless, looking at a broader scale, it is questionable if not rather the government should be responsible to provide sufficient infrastructure for water supply. From this point of view, it would be too high of an expectation, to pay-off tanks with revenues from gardening, and rather considerations of water and nutrition security as well as environmental benefits might be more important than a purely cost-benefit analysis.

6.7 Choice of indicators effecting sustainability

The outcome of the Sustainability Assessment depends on one side on results of this study and, as already discussed in chapter 6.5, the results of this study need to be verified. On the other side, the outcome of the Sustainability Assessment also depends on the choice of indicators employed. For this study the outcome was tested, if other indicators for the respective dimension would have been used. In fact, it resulted that the use of the ecologic indicator “output per input of water [kg/m^3]” compared to “water input per area [m^3/m^2]” gave a slight different ranking. While with the first indicator [kg/m^3] the low water scenario C2 was positioned at the 3rd rank, with the indicator m^3/m^2 it would be positioned at the 2nd rank. All other crop scenarios remain in the same rank. For the combined environmental and economic indicator, “revenue per cubic meter of water [N$/m^3]” a different ranking was found, since not only it includes yields and crop water requirement but also market prices. For this reason, crop scenarios with crops that can achieve higher prices, score better under this indicator. Using this combined indicator, the high risk scenarios (D1, D2) would lead the way, followed by the cash scenarios (B1, B2), the low water scenario (C2, C1) and finally the subsistence scenario (A1, A2). The exact scores are shown in Figure 58. Most sustainable would be crop scenarios that score high in water efficiency defined as output of crops per input of water (kg/m^3), score low on water efficiency defined as irrigation water per area (m^3/m^2) and score high in revenue per input of water (N$/m^3).

alternative ecologic indicator	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons
water efficiency [kg/m^3]	6.7	6.1	9.8	9.5	9.9	9.5	9.3	9.0
water efficiency [m^3/m^2]	0.558	0.605	0.403	0.408	0.373	0.383	0.431	0.443
revenue per m^3 [N$/m^3]	17	15	25	26	20	21	51	49

Figure 58: Comparison of two ecologic indicators and a combined ecologic-economic indicator (own calculation)

Changing the economic indicator “static payback time [years]” with the “dynamic prime costs [N$]” would also have a different outcome. As presented in chapter 5.2.2 “Economic cost- benefit analysis”, all tanks under all crop and climate scenarios would have negative net present values. This would imply that they are all economically not sustainable. Consequently using this indicator, all scenarios would have an overall outcome of being not sustainable. On the contrary, using the static payback time as indicator, the cash and the high risk crop scenario are yet sustainable. Nonetheless, the ranking of the crop scenarios for both of these sustainability indicators would remain exact the same. The indicator scores are shown in Figure 59.

	susbsitence		cash		low water		high risk	
alternative economic indicator	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons	1 season	2 seasons
static payback time [years]	61	70	32	35	44	44	19	22
dynamic net present value [N$]	-25,076	-26,352	-16,126	-18,002	-21,342	-21,419	-4,071	-7,743

Figure 59: Comparison of two economic indicators (own calculation)

6.8 Critical points

There is an important issue when comparing costs of rainwater harvesting facilities with the cost of connecting a household to a private tap. Villagers or the government would decide to invest in a rainwater harvesting facility if the costs of constructing and maintenance of the roof rainwater harvesting system are be lower than the cost of an equal amount of water from a private tap (Deffner et al. 2008: 19). However, this is not the case, as tap water currently costs 8.90 N$/ m³ while the cost of harvested rainwater from a ferrocement tank distributed over the lifespan would be around 27 N$/ m³, calculated with the dynamic prime cost method (Jokisch 2010: 27). Nevertheless, it should be kept in mind, that tap water in northern Namibia is currently subtracted from the far away Calueque Dam in Angola and the infrastructure and transport system are not fully integrated in the current tap water price.

Moreover, the use of dynamic methods with discounting rates to assess cost-benefit analysis is questionable. A discounting rate of 5% as used by this study represents the opportunity cost of capital, which implies that villagers could invest the money at a bank and achieve 5% of annual interest, instead of investing in rainwater harvesting facilities. However, due to the absence of banking services in the area and the mentality of the people of rather investing in a bigger herd of animals, this would probably not be the case. Therefore this study advocates for the use of a static method to assess costs and benefits.

If villagers have to undertake the burden of the initial investment all by themselves, it is questionable whether enough financial resources will be available. Even now, it is reported that some inhabitants of Epyeshona often prefer to walk more than 2 km to fetch water from a borrow pit in order to avoid the high costs of the closely situated communal water points (Deffner et al. 2008: 19).

In addition, a valuable lesson learned in the Laikipia District, Kenya concerning rainwater harvesting (Agarwal et al. 2001: 191), which was also sustained by numerous other authors such as Reed and Harvey (2004: 187), is that to be truly sustainable, poverty alleviation will only succeed if technical and environmental issues are balanced with equity and justice. In the context of this study, the issue of equity is raised by the fact that poorer inhabitants who would be the ones most in need for a rainwater harvesting facility, usually do not have private water taps. They are the ones who live in traditional huts without the necessary corrugated iron sheets for rainwater harvesting. Conversely, households which have corrugated iron roofs are often the ones to already have a private tap and may not be as interested or in need of a rainwater harvesting facility (Deffner et al. 2008: 19).

The acceptance of the technology is a precondition for success, since neither rainwater harvesting nor gardening is traditionally practiced in Namibia (Deffner et al. 2008: 7). Possible backdrops represent the insecure land tenure rules and access in northern Namibia (Werner 2009: 7 f), bureaucratic resistance and lack of governmental policies (Dima et al 2002: 12). Barriers for selling the produce at markets might be the fact that often a permit must be purchased to sell produce in the markets which costs a certain amount, whether or not produce is being sold (Deffner et al. 2008: 23 f). Concerns over theft of gardening products are widespread among gardeners in northern Namibia (Dima et al 2002: 12). Alcohol problems in the area, especially among men, (Lux and Janowicz 2009: 38) might be a barrier to engage in gardening activities if motivation is low. Yet they might see their chance and become motivated to engage in a productive activity.

6.9 Recommendations

At present, the rural residents in northern Namibia have little knowledge of rainwater harvesting methods and the initial costs are perceived as very high in relation to the amount of water that can be collected. Mutually shared investment models should be taken into consideration to overcome this (Deffner et al. 2008: 12). Furthermore it is recommended that the small growers should be assisted to organize themselves into producer cooperatives so that they can break into the main market (Dima et al. 2002: 15).

Based on the results from the Sustainability Assessment of the cropping and irrigation schemes, this study recommends to balance the different criteria in order to achieve the highest state of sustainability. Since sustainability depends strongest on the choice of crops, an optimized garden should contain several crops that score high on water efficiency, yield and market price and serve subsistence as well as market sale requirements.

The high risk garden, with only cucumbers, is not recommendable. It was conceived with the purpose to show how short the fastest payback time could possibly be. This was done, as the study found that the economic part was the biggest issue for a sustainable outcome.

As the ecological analysis in chapter 5.2.1 shows, even a high adoption rate of rainwater harvesting in the Cuvelai-Etosha basin is not likely to have a great impact on the natural water cycle. Hence, even if 100% of households in the basin would practice rainwater harvesting, this would harvest a maximum of 0.016% of the rain, of which 83% would have anyway been lost to the atmosphere through evaporation. Based on this aspect, this study can recommend the broad spread of rainwater harvesting in the basin.

7 Conclusion

The objective of the study was to elaborate how rainwater harvesting systems can be used for the irrigation of gardens in a sustainable manner. The study started with 30 m³ tanks built by the CuveWaters project and a roof catchment area of 100 m². According to the amount of harvested rainwater cropping and irrigation schemes with different crop scenarios under present and future climate scenarios were optimized. It resulted, that depending on crop scenario under optimized conditions a garden area of 60 to 90 m³ can be planted. The choice of crops has the highest influence on water use, followed by number of planting seasons per year and last by the impact of future climate change. For worsening future climate conditions, adaptation measures need to be taken, since on one side a lower proportion of crop water requirement will be satisfied directly from rain while on the other side less rainwater will be harvested and available for irrigation. Although under future best climate change garden area could be in part slightly enlarged, achieving slightly higher yields and revenues, the clearer picture is that the garden area will have to be gradually reduced, in part considerably, in the next 40 years until 2050. This is true for the future medium and especially for the worst climate scenario, leading to lower yields and revenues.

The most limiting factor to sustainability is the economic dimension for this case study at pilot stage, especially the investment costs of the rainwater harvesting and gardening facility, while the environmental and the social dimension can be generally perceived as sustainable. With climate change, the economic situation is expected to exacerbate, as with worsening conditions yields and revenues will decrease and payback time increase. Also the environmental dimension will be impacted negatively by climate change, as with expected decrease in precipitation, irrigation requirements will increase, lowering the irrigation water efficiency, meaning more irrigation water per unit of output.

Nonetheless, rainwater harvesting in combination with gardening can be perceived as successful in securing household nutrition, providing sufficient horticulture products for consumption. At the end of the lifespan of the facility the investment costs can be even recovered, whether through market sale or through saved expenses, if the right crops were planted. A precondition for this however remains finding a financing model that solves the individual burden of high investment costs.

As outlook for future research the study proposes the creation of an optimal crop and irrigation scheme that optimally combines the three sustainability dimensions, considering a higher number of indicators. However, as already shown by this study, it is quite difficult to reconcile different criteria and with a growing number of indicators complexity will even augment.

IV Appendix

The appendix can be found in electronic form on the following CD. Its content is described in the following Table:

Name of file	Contents
Climate data	Analysis of all relevant climate data
Tank model and scenarios	Irrigation Requirement Dropping and irrigation schedules for each crop scenario under present climate conditions with yield, revenues and water efficiency. Tank model for each crop scenario under present and future climate scenarios with area optimized for present climate Cost-benefit analysis
Area optimization	Optimization of the garden area for each crop scenario under the three future climate scenarios with the tank model

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VI Author´s Declaration

Unless otherwise indicated in the text or references, this thesis is entirely the product of my own scholarly work. Any inaccuracies of fact or faults in reasoning are my own and accordingly I take full responsibility. This thesis has not been submitted either in whole or part, for a degree at this or any other university or institution.

Frankfurt,