University of Hohenheim

Faculty of Agricultural Sciences

Institute for Plant Production and Agroecology in the Tropics and Subtropics

Crop Water Stress Management in the Tropics and Subtropics (380c)

JATROPHA CULTIVATION USING TREATED SEWAGE EFFLUENT

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WATER REQUIREMENTS AND ENVIRONMENTAL RISKS

(A CASE OF SOUTHERN MOROCCO)

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Thesis submitted in partial fulfilment of the requirement for the award of Master of Science degree in Agricultural Sciences

Hohenheim, September 2010

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ABSTRACT

Water is becoming increasingly scarce in Morocco. In contrast to the country's decreasing freshwater resources, the amount and availability of wastewater will strongly increase in the next years. The main share of the Moroccan sewage effluent currently experiences secondary treatment resulting in nutrient-rich treated sewage effluent (TSE). The production of energy crops such as *Jatropha curcas* on marginal soils is discussed as a supplemental wastewater treatment. In order to evaluate the suitability of Jatropha cultivation in a combined plant production / effluent treatment system, its water requirements were calculated using CROPWAT 8.0. Based on the resulting irrigation requirements on a sandy soil in Southern Morocco, the nutrient inputs from the TSE were compared to the potential nutrient export from biomass harvesting. The crop evapotranspiration (ET_c) during one growing period (February-August) was calculated to be 767 mm. The nutrient import from the basic irrigation requirements was equal to the theoretical nutrient stock in ~4 t of Jatropha fruits for N and P, and ~7 t of fruits for K. The gross irrigation requirements ranged from 868-1,329 mm. The corresponding nutrient inputs from the effluent were 84-129 kg ha^{-1} for N, 24-37 kg ha^{-1} for P, and 169-259 kg ha^{-1} for K, respectively. The amount of wastewater produced by the treatment plant would allow irrigation of approximately 52 to 69 ha of Jatropha. The average soil salinity in the root-zone was between 2 dS m^{-1} and > 9 dS m^{-1} depending on the leaching fraction. Additional challenges are caused by the fact that Jatropha is reported to shed its leaves in the winter season and thus stops transpiration. This could be accounted for by intercropping activities. To validate the results in practice, the agronomic properties of Jatropha such as crop salinity tolerance, water requirements, and nutrient requirements need to be the subject of further research activities.

Keywords: Effluent irrigation, *Jatropha curcas*, Morocco, Water requirements, N-P-K balance

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LIST OF ABBREVIATIONS

AH	Air humidity
ARWR	Annual renewable water resources
BOD	Biochemical oxygen demand
Ca^{2+}	Calcium ion
Cl^-	Chloride ion
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DM	Dry matter
DOM	Dissolved organic matter
dS	DeciSiemens
EC	Electrical conductivity
EC_e	Electrical conductivity of the soil solution extract
ECsw	Electrical conductivity of the soil water
EC_w	Electrical conductivity of the irrigation water
ESP	Exchangeable sodium percentage
ET_0	Reference evapotranspiration
ET_c	Crop evapotranspiration
$ET_{c\ adj}$	Adjusted crop evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GJ	Gigajoule
IfaS	Institut für angewandtes Stroffstrommanagement
IR	Irrigation requirement
IRg	Gross irrigation requirement
K^+	Potassium ion
K_c	Simple crop coefficient
K_{cb}	Basal / Transpiration crop coefficient
K_e	Soil evapotranspiration coefficient
$EC_{e\ max}$	Soil salinity threshold determined in the saturation extract
Kg	Kilogram
K_s	Water stress coefficient
L	Litre
LF	Leaching fraction
LR	Leaching requirement
MAP	Mediterranean Action Plan
MENA	Middle East and Northern Africa
Mg	Milligram
Mg^{2+}	Magnesium ion
Mm^3	Million cubic metres
N	Nitrogen
Na^+	Sodium ion
NH_4^+	Ammonium
N_{min}	Mineral N
NO_3^-	Nitrate
O_2	Oxygen
ONEP	Office National de l'Eau Potable
P	Phosphorous
P_2O_5	Phosphorous pentoxide
PAW	Plant available water
PNA	Programme National d'Assainissement liquide, de traitement et de réutilisation des eaux usées

PO_4^-	Phosphate
RSE	Raw sewage effluent
SAR	Sodium adsorption ratio
SEOR	Société des Eaux de l'Oum Ribâa
T	Ton
TAM	Total available moisture
TDS	Total dissolved solids
T_{max}	Maximum temperature
T_{min}	Minimum temperature
TN	Total Nitrogen
TSE	Treated sewage effluent
TSS	Total suspended solids
UN	United Nations
UNSODA	Unsaturated soil hydraulic database
USDA	United States Department of Agriculture
WF	Water footprint
WHO	World Health Organization
WUE	Water use efficiency
WWTP	Wastewater treatment plant

1 INTRODUCTION

Morocco's energy supply is based almost entirely on the import of fossil fuel, with its fluctuating prices and negative effects on the environment. Being aware of these problems, Morocco is among the first African countries to have passed legislation on renewable energies (law 13-09). In this context, also the production of plant biomass for energetic uses such as anaerobic digestion or combustion (e.g. solid fuels, plant oil) raises interest (WBGU 2009).

However, water scarcity poses a problem in Morocco and is made worse by the currently increasing intensification of agriculture. Through an initiative that is subsidised by the government (*plan vert*), huge areas are converted from rain-fed cereal cropping to irrigated cultures like olives or citrus fruits.

At the same time, because of the increase in urbanisation, a national programme targets the installation of sewage systems (AHT Group AG 2009). Globally, wastewater is the only water source of which the amount and availability will increase in the next years (World Water Assessment Programme 2009). Wastewater treatment in Morocco is a sector that mostly causes costs but does not produce added value to the region. The applied treatment systems generally have a low energy demand and produce only secondary treated effluent (AHT Group AG 2009, FAO Wastewater Database 2002). This effluent contains a considerable amount of nutrients (N-P-K) which can cause pollution / eutrophication when disposed of in surface waters (Toze 2006). However, in crop production systems, these nutrients represent precious resources in times of rising prices for fertilizers and decreasing fossil resources (for example Phosphorous).

To make the utilisation of resources (e.g. water and nutrients) more efficient, they can be subject to a cascade use (WBGU 2009). This means that each step of the resource consumption is linked to utilization. The production of biomass in order to remove nutrients from the wastewater by creating a regenerative source of energy is such a possibility. *Jatropha curcas*, a tropical oil crop, is being discussed in this context. Besides Jatropha's low site requirements, its multiple potentials in biomass production make it an intriguing plant (Francis et al. 2005). Apart from the production of oil-rich seeds, by-products such as pruning material and press cake can be used as a co-substrate in anaerobic digestion in biogas plants (Achten et al. 2008, Gunaseelan 2009).

However, effluent irrigation is discussed controversially. Treated sewage effluent (TSE) differs from freshwater because of its microbiological, physical and chemical properties (Feigin et al. 1991). The use of TSE in plant production can cause the build-up of soil salinity, changes in soil structure and nutrient leaching (Da Fonseca et al. 2007). In effluent irrigation, the irrigation amount directly controls the matter input. Hence, the irrigation requirements of Jatropha are the base to identify challenges and potentials of effluent irrigated plantations in semi-arid climates.

In this study, the following questions were addressed: If Jatropha was to be used in biomass production and wastewater treatment on a marginal soil in Southern Morocco, how high are its water requirements? What is the nutrient balance like? What problems (e.g. salinity and sodicity) could result in the long term?

2 HYPOTHESIS & OBJECTIVES

It is possible to grow Jatropha in the semi-arid climate of Southern Morocco (sustainable, nutrient efficient, and environmentally sound) to achieve a combination of supplemental effluent treatment and biomass production.

The following hypotheses were adopted:

(i) The water requirements of Jathropha plants under Southern Moroccan climate correspond to the amount of secondary treated sewage effluent that is produced by small to medium sized cities in Morocco,

(ii) The nutrient requirements (or: potential nutrient exports) have an appropriate ratio to the nutrient inputs from the TSE, and

(iii) TSE can be used in long-term Jatropha irrigation without causing high salinity and sodicity levels in the soil.

3 BACKGROUND

3.1 Water in Morocco

Every year, an average of 145 billion m^3 of water precipitates on Moroccan territory. Almost 80% (~123 billion m^3) of the total precipitation evaporates, returning to the atmosphere as water vapour (FAO 2005). Of the remaining 22 billion m^3, 18 billion m^3 contribute to surface waters and 4 billion m^3 to groundwater stocks. According to the MEDA report from 2009 (AHT Group AG 2009), almost 20.7 billion m^3 of the annual renewable water resources (ARWR) can be mobilized under current technical and economic conditions.

The "Falkenmark Indicator" can be used to rank Morocco's average water availability of 730 m^3 $capita^{-1}$ a^{-1}. It is the widest applied water scarcity index and is based on an approximate minimum level of water required per capita to maintain an adequate living standard in a moderately developed country (Qadir et al. 2010a). The threshold is set at 1000 m^3 of ARWR $capita^{-1}$. Countries having a lower ARWR are likely to suffer from serious water shortages. These impact on economic development, human health and wellbeing. With an ARWR of less than 500 m^3 $capita^{-1}$, a country experiences "absolute water scarcity". Due to different climatic conditions in Morocco, water availability varies considerably from up to 1,850 m^3 a^{-1} in the Northern parts to less than 100 m^3 a^{-1} in the extreme South (UN Water Africa 2004).

3.1.1 Water withdrawal

Owing to the relatively high precipitation (compared to other countries of the Middle East and Northern Africa, MENA) and numerous watercourses originating from the mountainous relief, Morocco successfully established an extensive barrage system. More than 100 reservoirs with a total storage capacity exceeding 16.3 billion m^3 have been created to ensure water supply all year round (AHT Group AG 2009).

At present, the total annual water withdrawal in Morocco equals 13 billion m^3 a^{-1}. The minor share of non-conventional water resources, such as wastewater and desalinated water, is estimated to average 0.5 and 0.007 billion m^3 a^{-1}, respectively (FAO 2005, AHT Group AG 2009). In 2000, the agricultural sector was responsible for approximately 87% of the total water withdrawal in Morocco, followed by the domestic and the industrial sector with around 10% and 3%, respectively (Figure 1, Table 1). The FAO projections for 2020 (FAO 2005) foresee that the total national water withdrawal will increase to 24%. Due to the country's limited and partly over-exploited freshwater resources, the agricultural use of non-conventional water such as treated sewage effluent (TSE) becomes an urgent necessity.

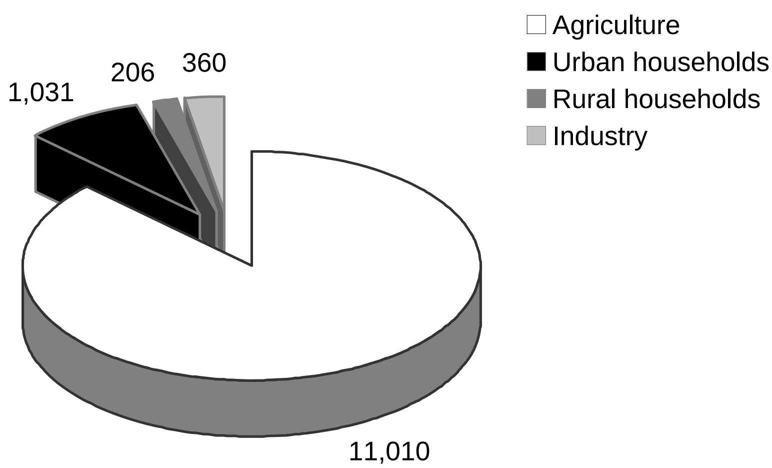

Figure 1: Water withdrawal (in Mm^3) of the agricultural, the domestic, and the industrial sector in Morocco.

The agricultural sector

Currently, the agricultural sector accounts for more than 85% of the country's total water consumption and has by far the greatest influence on the annual water balance in Morocco. Most of the irrigation water is dedicated to the production of vegetables, citrus and industrial crops such sugar beet, sugar cane, and cotton (FAO 2005).

In 2000, the agricultural water withdrawal in Morocco equalled ~11,010 million m^3 (Mm^3). Surface water provided the main share of ~75% (~8,273 Mm^3 a^{-1}), whereas groundwater withdrawal accounted for ~25% (~2,738 Mm^3 a^{-1}).

Due to the extreme variations both in interannual and seasonal precipitation, rain fed agriculture is subject to considerable yield fluctuations. For instance, the yield of cereal (cereal production occupies 68% of the non-irrigated agricultural surface) varies between 2 and 10 million tons per year. Hence, irrigated agriculture in Morocco plays a major role in securing both the national agricultural production and food security.

In 2004, the surface equipped for irrigated agriculture occupied 1,459,000 ha, which makes up ~17% of the total cropping area in Morocco (FAO 2005). Since the 1960s the government substantially supports irrigated agriculture by preparing extensive areas, installing irrigation systems, and managing water supply. Of a total of 1,459,000 ha irrigated surface, 70% have been established by public agencies.

The domestic sector

Moroccan households account for a total water withdrawal of 1,237 Mm^3, representing almost 10% of the total water demand. This amount is going to increase due to population growth, rising living standards, industrialisation, and urbanisation. Most likely, the supplemental water will be extracted from the agricultural sector (Qadir et al. 2010b).

The domestic water consumption in Morocco differs greatly between urban and rural areas. The average daily consumption of a rural individual is about 20 L per day, whereas the average urban individual consumes as much as 90 L.

Table 1: Annual water consumption of the agricultural, domestic, and industrial sector in Morocco in 2000 and projections for 2020 (in million m^3, Mm^3) (FAO 2005, AHT Group AG 2009).

Sector	**Water consumption in 2000** [Mm^3]	**% Total water use**	**Water consumption in 2020** [Mm^3]	**% Total water use**	**Difference**
Agriculture	11,010	87.3	13,039	82	+ 18%
Domestic	1,237	9.8	2,201	14	+ 78%
Urban households	*1,031*	*8.2*	*1,949*	*12*	*+ 89%*
Rural households	*206*	*1.6*	*252*	*2*	*+ 22%*
Industry	360	2.9	450	3	+ 25%
Total	**12,607**	**100**	**15,690**	**100**	**+ 24%**

Drinking water is mainly provided by the ONEP (Office National de l'Eau Potable), supplying roughly 80% of Moroccan households. The SEOR (Société des Eaux de l'Oum Ribâa), autonomic municipal providers, and private concessionaires supply the rest.

3.1.2 Wastewater production, treatment and reuse

The wastewater volume produced by the urban areas of Morocco is in the range of 650 Mm^3 a^{-1} (FAO Wastewater Database 2002). In contrast to other MENA countries (like Algeria or Tunisia), Morocco has no central authority for wastewater treatment. Currently, the law 78-00 from October 2002 assigns the responsibility for wastewater disposal, treatment, and prevention of pollution, to the local communities (AHT Group AG 2009). Only a few communities are able to deal with this task because of the limitation in human, material, and financial resources. Consequently, most communities render the task to either the ONEP (the national drinking water office) or to private operators.

The current prizing system for wastewater collection and disposal includes a fixed and a variable unit, with the latter depending on the quantitative consumption of drinking water. Even though tariffs vary regionally, the World Bank identified an average prize of 2 Dirham m^{-3}, corresponding to ~30% of the charges for potable water supply (World Bank and KfW 2007). The same study revealed that this price would only cover 22% of the total emerging costs.

Despite the fact that the “polluter payer” principle is enacted by the water law 95-10, it has not yet been applied in Morocco. Similar to domestic consumers, industrial units are charged by the amount of effluent disposed instead of its composition. As a result, several wastewater treatment plants (WWTP) suffer from perturbations of the treatment process caused by highly polluted industrial effluent.

At present, the vast majority of Moroccan wastewater does not receive any treatment but is directly discharged into the sea, the rivers, the Oueds or is allowed to infiltrate into the soil. This practice causes pollution of coastal ecosystems, substantial degradation of regional surface and decline in groundwater quality. Estimations of the Mediterranean Action Plan (MAP) assume that nation-wide around 55% (~360 Mm^3) of the urban wastewater is dumped directly into the Atlantic Ocean (52%) or the Mediterranean Sea (3%) (MAP 2007). Although 73% of the Moroccan households are connected to an improved sewage system, only 13% (~84.5 Mm^3) of the produced effluent receives secondary treatment (World Bank and KfW 2007, OIEau 2007) (Figure 2).

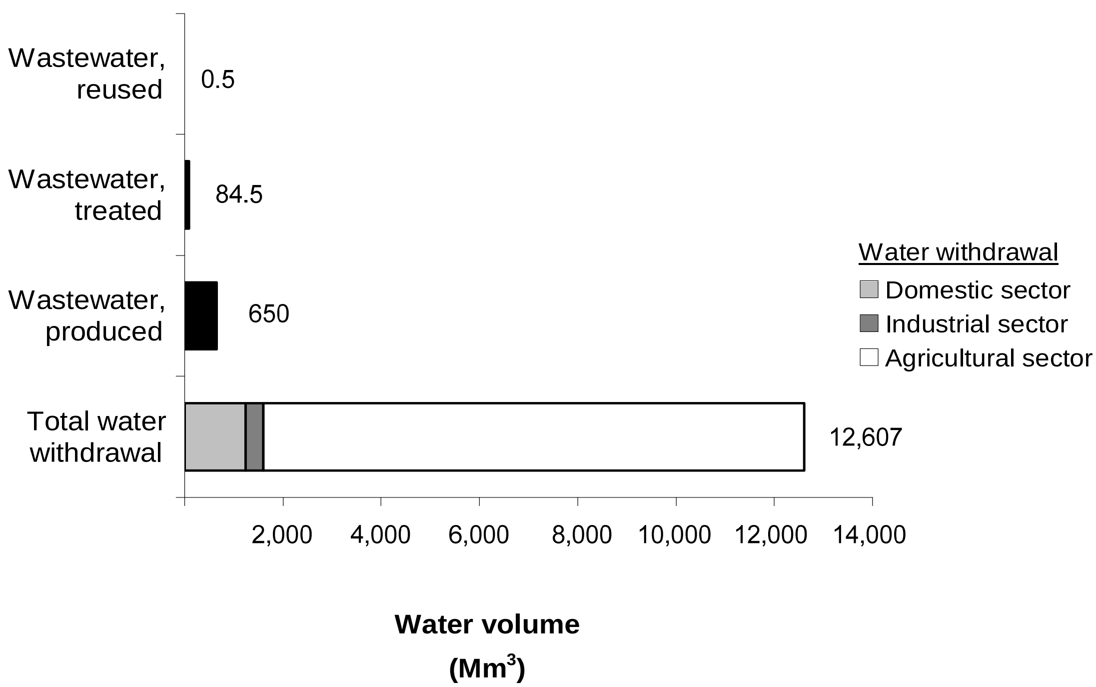

Figure 2: Total water withdrawal from agriculture, households, and industry in Morocco, and shares of wastewater that is collected in sewage systems, treated, and reused (in million m^3, Mm^3).

Many of the older WWTPs in Morocco are out of service mainly due to a common unwillingness to invest in the wastewater sector. Furthermore, population growth, rising living standard, and rapid urbanization increase the pressure on existing WWTPs, which are under-dimensioned for the high effluent charges. Hence, many treatment plants are being operated well beyond their capacity, resulting in insufficient purification and frequent breakdowns (Qadir et al. 2010b).

Being conscious of the environmental problems resulting from raw wastewater disposal, the Moroccan government and the ONEP agreed on the National Wastewater Management Plan (*Programme National d'Assainissement liquide, de traitement et de réutilisation des eaux usées,* PNA*).* The programme was launched in 2005 and schedules considerable investments in sewage systems and wastewater treatment. For 2020, the PNA appoints two specific objectives:

(i) To connect 80% of the urban population to a collective sewage system, and

(ii) To reduce pollution by 80%.

Even though the PNA stresses the importance of developing the potential of treated sewage effluent (TSE) as a supplemental water source, reuse does not range between the programme's priorities. However, the ONEP in cooperation with the FAO has already identified a number of wastewater treatment plants suitable for the reuse of TSE in agriculture (ONEP and FAO 2007).

The increasing number of treatment plants which only apply secondary treatment produces large volumes of nutrient rich effluent. More than 90% of the Moroccan treatment plants are designed as stabilization pond systems (*lagunage*). Due to its simple operation and construction, cost effectiveness, low maintenance, and energy requirements, this system is common in small to medium sized cities of developing countries with a warm climate and no land limitations (Feigin et al. 1991).

Usually, the stabilization pond system is divided into two different stages: the anaerobic stage (primary treatment) and the facultative stage (secondary treatment) (Pescod 1992). During the primary treatment, organic and inorganic solids, greases and oils are removed. As a result, the biochemical oxygen demand (BOD) decreases. The anaerobic ponds have a high volumetric rate of removal, but the slow degradation of organic matter causes odour nuisance due to the formation of hydrogen sulphide (Da Fonseca et al. 2007).

The secondary treatment takes place in the facultative ponds. These ponds are larger in area and relatively shallow. They are characterized by aerobic (oxidation) processes in the surface layer and anaerobic processes in the deeper layers. During the secondary treatment, most of the remaining organic matter is removed by coordinated activity of algae and (heterotrophic) bacteria. The photosynthetic activity of the algae generates oxygen, which the bacteria (aerobic or facultative) use to oxidize the organic compounds in the wastewater. The bacterial degradation releases nutrients and CO_2 that then is fixed in the algal biomass. As a result, the organic compounds of the effluent take more stable forms (Feigin et al. 1991).

The wastewater treatment process generates two different residue types: (i) sewage sludge (biosolids) and (ii) secondary treated effluent. The former will not be discussed here and the latter will be referred to as treated sewage effluent (TSE).

TSE has a potential to be valued in plant production systems by delivering simultaneously water and nutrients (ONEP and FAO 2007). Moreover, the soil-plant system retains nutrients and thus reduces matter export, which could otherwise adversely affect surface and groundwater quality.
Generally, the water quality of the Moroccan TSE does meet the national water quality discharge consent, but it does not fulfil the quality norms for unrestricted use as set by the WHO in 2006 (WHO 2006). Some examples for chemical compositions of secondary TSE are given in Table 2.

Table 2: Average values for physical and chemical characteristics of treated sewage effluent (TSE) from different studies in the world (Da Fonseca et al. 2007).

Constituent	Unit	Range in TSE
pH		7.8-8.1
EC	(dS m^{-1})	1.0-3.1
TSS	(mg l^{-1})	-
N_{min}	(mg l^{-1})	10-50
PO_4 P	(mg l^{-1})	4.2-9.7
K^+	(mg l^{-1})	10-40
Cl^-	(mg l^{-1})	-
Ca^{2+}	(mg l^{-1})	20-120
Mg^{2+}	(mg l^{-1})	10-50
Na^+	(mg l^{-1})	50-250

The discharge of TSE in surface water streams can cause considerable environmental damage and should be restricted (Bond 1998). One option to limit the adverse effects of TSE disposal would be a tertiary treatment of the effluent. Since this is a costly technology (both investment and energy costs), cheaper alternatives such as soil application of TSE in plant production systems represent potential solutions (Darwish et al. 1999, Christen et al. 2010).
At the moment, neither the exact TSE volume used in Moroccan agriculture nor the size of the irrigated surface is known. Most of the Moroccan experience in TSE-reuse is limited to small scale pilot projects such as Ouarzazate (lagoon system), Ben Slimane (aerated lagoon) and Drarga (infiltration, percolation). Aside from a few projects that have been realized in the tourism sector (hotels, golf courses), no large-scale reuse of TSE has been documented in Morocco (AHT Group AG 2009). Within the PNA (national wastewater management plan), several projects have been launched (e.g. in Agadir, Tiznit, and Casablanca), but results are not available as yet.

4 STATE OF THE ART

The agricultural use of TSE is a common practice in water scarce areas of arid and semi-arid countries (e.g. USA, Mexico, Australia, MENA Countries, China) (Feigin et al. 1991). The main benefits of effluent irrigation are (i) additional water supply in regions lacking freshwater (Qadir et al. 2010a), (ii) fertiliser substitution by the effluent's nutrient load (Al-Nakshabandi et al. 1997, Ryan et al. 2006, Leal et al. 2010), and (iii) supplemental treatment for wastewater (Pollice et al. 2004).

In sewage systems, water is solvent and the mean of transportation. In plant production systems, it is the most crucial component for plant growth. Due to its liquid nature, it moves almost barrier-free through natural environments. In regions with high solar radiation intensities and high vapour pressure deficits, water evaporates quickly, leaving higher matter concentrations in the remaining solution. The physical and chemical properties of water make effluent irrigation a complex system with multiple parameters, interactions, and reactions. As the actual irrigated surface represents only a fraction of the regional water cycle, a sustainable approach needs to take up- and downstream issues into account (Huibers and van Lier 2005). The overall sustainability of individual TSE irrigation projects is controlled by technical, socio-economic, environmental, and economic factors (Huibers and Raschid-Sally 2005) (Figure 3).

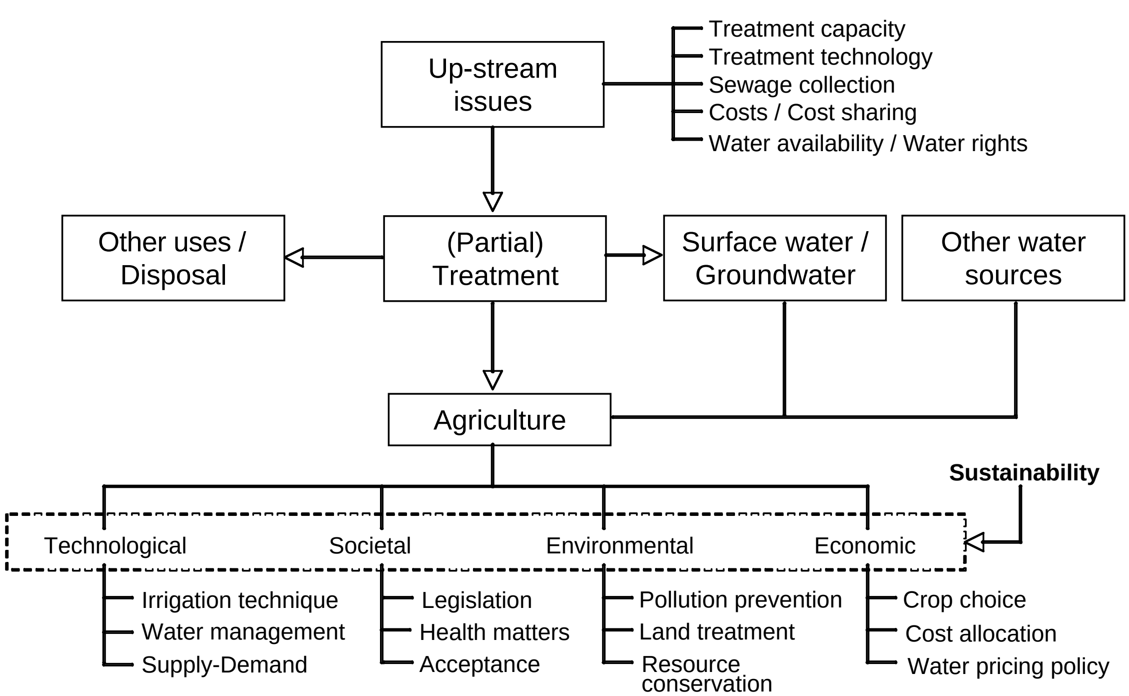

Figure 3: Conceptual framework for sustainable use of treated sewage effluent in agriculture (after Huibers and Raschid-Sally 2005).

In Morocco, irrigation with TSE is not yet common. This is mainly due to the small number of adequate treatment plants and to the inhibiting political, administrative and logistical conditions (AHT Group AG 2009) (see 3.1.2). Given the situation of increasing water and energy shortages (MAP 2007), several programmes have been launched to address these problems. These include the promotion of renewable energies and the development of the wastewater sector (see 3.1.2). This trend in Moroccan politics gives rise to reinforced discussions on the cultivation of energy crops with wastewater irrigation.

During the last years, several unexplored oil-crops, such as Pongamia (*Pongamia pinnata*) Jojoba (*Simmondsia chinensis*) and Jatropha (*Jatropha curcas*) have been promoted for plant oil production in semi-arid regions of the tropics and subtropics (Chang and Su 2010). Especially Jatropha is claimed to grow on marginal soils, which is of great interest for effluent irrigation. For economic reasons, TSE irrigation water needs to be applied in proximity to the wastewater treatment plants (ONEP and FAO 2007). The soils around these are often unfavourable. That is why hardy plants with low site and water quality requirements are needed.

According to a worldwide study on Jatropha, no production areas have yet been identified in Morocco (GEXSI LLP 2008). But with the increasing popularity of Jatropha, its cultivation is now considered in green belts around cities or in soil-plant systems to treat wastewater (IfaS 2009). Due to its growing importance and the potential use in Moroccan projects, Jatropha will be discussed in detail.

Jatropha curcas L. is a perennial, stem-succulent, deciduous shrub producing oil-rich seeds (Foidl et al. 1996). These seeds can easily be converted into liquid bio-fuels meeting international standards (Azam et al. 2005). Additionally, the organic residues (pruning material, press cake, seed husks) can either serve as a fertilizer or can be digested to produce biogas (Achten et al. 2008, Gunaseelan 2009). In the current search for alternative fuel sources, Jatropha received a lot of attention due to its ability to grow on marginal dry-land. It is believed to reduce the competition between energy-production and food-production by taking “wasteland” into cultivation (Francis et al. 2005, Asch and Huelsebusch 2009). Recently, high seed yields (~5 t ha^{-1} a^{-1}) and high oil contents boosted the great expectations in Jatropha (Achten et al. 2010a). The plant has a variety of uses (soap production, lubricant, medicinal use, etc.) (Heller 1996). If adequately managed, its cultivation has the potential to reclaim degraded land having a positive impact on biodiversity and soil resources (Francis et al. 2005). Before its large-scale cultivation, Jatropha was claimed to be pest resistant and high yielding, while having low input requirements (Jongschaap et al. 2007).

Based on all these ideas, Jatropha takes a special place among the tropical biofuel crops and its expansion accelerates. In 2008, more than 900,000 ha of Jatropha plantations have been identified worldwide. In 2010, the area is expected to reach 5 Million ha (GEXSI LLP 2008).

However, most of the plantations are still immature (<5 years) and oil yields are not yet significant (Achten et al. 2008).

In contrast to the speed with which Jatropha plantations have been established, the accompanying research develops slowly. Science still lacks important findings (Openshaw 2000, Fairless 2007). Even though there have been some results in the fields of biology and genetics (e.g. Ginwal et al. 2004, Saika et al. 2009, Divakara et al. 2010), Jatropha remains a non-domesticated plant and large scale plantations bear incalculable risks (Achten et al. 2010b). There are knowledge gaps in its basic agronomic properties, mainly water requirements (Jongschaap et al. 2007, Achten et al. 2008, Maes et al. 2009a), salinity tolerance (Dagar et al. 2006), and growth and yield response to input (Maes et al. 2009b).

An alternative use for Jatropha could be the cultivation on marginal soils at close range of wastewater treatment plants. As a treelike and non-food crop, the hygienic requirements for the TSE irrigation are relatively low, especially when micro irrigation is used. The cultivation of Jatropha generates biomass (nuts, pruning material) that, if sold, could be used to partly cover the costs of wastewater treatment. In addition, the energetic use in local systems (e.g. biogas plants, plant oil production) can increase regional independence from fossil fuel markets and create added value.

Beside economic benefits for the plant growers (Segarra et al. 1996) and the mitigation of water scarcity, the application of TSE to soil-plant systems provides supplemental wastewater treatment. The soil-plant system acts as natural filter by absorbing and fixing nutrients (mainly N and P). In this way, it reduces the discharge of nutrients to water bodies and thereby the pollution of surface water and groundwater (Pollice et al. 2004). Properly managed, TSE-irrigation represents an ecologically sound method of wastewater disposal (Toze 2006). However, the efficiency of water purification from the soil-plant system is controlled by several factors that need to be considered:

(i) Microbiological quality and chemical constitution of the effluent (WHO 2006), especially salt- (Mujeriego et al. 1996) and Na-concentrations (Bond 1998), heavy metals and nitrate (NO_3^-)-concentrations (Jordan et al. 1997);
(ii) Crop choice and yield expectations (Da Fonseca et al. 2007);
(iii) Nutrient concentrations in the effluent, TSE quantity / scheduling, and additional fertilizer application (Janssen et al. 2005);
(iv) Chemical, physical and microbiological soil properties (Bond 1998, Balks, 1998, Friedel et al. 2000); and
(v) Irrigation technique (Oron et al. 1999).

The wastewater officially claimed for reuse is mostly obtained after secondary (biological) treatment (Lado and Ben-Hur 2009, Qadir et al. 2010a). Due to the lack of tertiary treatment, most nutrients (especially nitrate-N and P) remain in the effluent. In Morocco, the predominant wastewater treatment system is the stabilization pond system (*lagunage*). Typically, the produced TSE comprises 99.9% water and 0.1% organic and inorganic compounds in a suspended or dissolved state (Pescod 1992). Despite their low percentage, these compounds considerably influence the effluent's chemical characteristics, such as electrical conductivity (EC), sodium adsorption ratio (SAR), pH, nutrient and microelement concentrations, dissolved organic matter (DOM), and total suspended solids (TSS).

Irrigation with TSE has been found to affect chemical, physical, and microbiological soil characteristics (Balks 1998, Bond 1998, Friedel et al. 2000). The magnitude of these changes is subject to the local conditions such as soil type, crop, and climate (Bond 1998, Shahalam et al. 1998, Da Fonseca et al. 2007). Other important parameters are the general freshwater availability, the quality of the TSE, and the irrigation scheduling. Depending on the environmental conditions and the cropping system, there may be significant impacts on the soil quality (Tabatabaei and Najafi 2009) or no (Wang et al. 2003).

With a given water quality, the quantity of the matter input is determined by water application depth and timing. This in turn depends on the crop's water requirements varying according to the crop's development stage, climate, and site conditions (Allen et al. 1998).

The water requirements of Jatropha have been subject to various discussions. There is a general agreement that the plant can thrive under a wide range of rainfall regimes, usually between 300 and 1,500 mm (Openshaw 2000). The opinions and research results about the optimum water requirements of Jatropha differ widely. Daey Ouwens et al. (2007) grouped the annual rainfall requirements for Jatropha in three categories: (i) 300 mm as the lower limit for survival, (ii) 600 mm as the lower limit for seed production, and (iii) 1,000-1,500 mm for optimum growth and seed production. In contrast, Gunaselaan (2009) stated that in India the optimum growth conditions for Jatropha were at precipitation levels below 600 mm a^{-1}.

An even lower water requirement resulted from a study on water use efficiency (WUE) of Jatropha in Egypt. The authors pointed out, that Jatropha could produce full yields with an irrigation water supply of only 44.5 mm ha^{-1} and vegetation period (Abou Kheira and Atta 2008).

In contrast, a study on Jatropha's climatic growth conditions in its area of natural distribution revealed that the great majority of the studied specimen grew in areas with mean annual precipitations above 944 mm (Maes et al. 2009b). According to Maes et al. (2009b) this explains why Jatropha rarely occurs in arid to semi-arid regions.

General characteristics of the plant's water relation show that Jatropha belongs to the deciduous stem succulent species and has a clear drought avoidance strategy in its leaves (Achten et al.

2010b). Similar to other stem succulent species, Jatropha strongly controls its stomatal conductance enabling relatively high transpiration efficiencies (~5.8 mg g^{-1}) and a conservative water use (Maes et al 2009c). Recent research suggests, that the plant's WUE is relatively high (Maes et al. 2009a) and its water footprint relatively low (Jongschaap et al. 2009, Maes et al. 2009b).

However, the water footprint (WF) of biodiesel from Jatropha has been subject to various heated discussions. Gerbens-Leenes et al. (2009) used the (non-peer reviewed) data of Daey Ouwens et al. (2007) to calculate the WF of bioenergy from different crops. According to their calculations, biodiesel from Jatropha had a greater WF (600 m^3 GJ^{-1}) than biodiesel obtained from soybean and rapeseed (400 m^3 GJ^{-1}). Jongschaap et al. (2009) opposed this with an adjusted calculation of the WF of Jatropha. By using field data from Gush and Moodley (2007), they implemented a water flow model and calculated a WF of 128 m^3 GJ^{-1}. Maes et al. (2009c) suggested a WF of only 65 m^3 GJ^{-1}. In their opinion, this magnitude of the WF is in line with recent scientific findings on plant-water relationships of Jatropha (Maes et al. 2009a).

The above-mentioned differences in calculating the water footprint of bioenergy from Jatropha illustrate great uncertainties concerning optimum water supply and yield responses to drought stress.

In general, the plant water requirements under optimum water supply (standard conditions) can be calculated by using the crop coefficient approach (Allen et al. 1998). So far, only very few studies have examined the water consumption of Jatropha in detail sufficiently to be able to calculate single crop coefficients (K_c) or transpiration crop coefficients (K_{cb}). For instance, in South Africa, Gush and Moodley (2007) conducted sap-flow measurements. They yielded annual transpiration totals of about 144 and 330 mm ha^{-1} and K_{cb} between 0.04-0.26 and 0.15-0.76, for 4 and 12 year old trees, respectively. The latest information on Jatropha's K_{cb} resulted from a greenhouse study, and delivered a value of 0.54 for immature Jatropha plants under optimum water supply (Achten et al. 2010b).

Since the economic interest in Jatropha is relatively recent, crop coefficients under different climatic conditions have not been established yet. More experimental results, both in greenhouses and in the field, are required to facilitate proper plantation planning and management. In case of TSE irrigation the water requirements of the culture are crucial to calculate matter input and leaching requirements. The two characteristics are essential to evaluate both potential environmental risks and economic feasibility of TSE irrigation.

Wastewater irrigation to mitigate water scarcity: Most important parameters Na and EC

From an agronomic point of view, high salt and Na-concentrations are the most problematic constituents in TSE (Da Fonseca et al. 2007, Lado and Ben-Hur 2009). Soil salinity is a prevalent abiotic stress for plants, especially in arid and semi-arid areas (Corwin et al. 2006). High salinity levels interfere with plant water uptake by decreasing the osmotic potential of the soil solution. Additional effects on plants can be nutrient imbalances and plant toxicity (Kijne et al. 1998).

The increase in soil salinity resulting from TSE irrigation has been widely reported for agricultural crops (Johns and McConchie 1994, Al-Nakshabandi et al. 1997, Gloaguen et al. 2007) and forest plantations (Cromer et al. 1984, Stewart et al. 1990, Falkiner and Smith 1997). Generally, soil EC was higher in the topsoil after wastewater irrigation (Biggs and Jiang 2009) and increased with its duration (Rusan et al. 2007).

Plants have different possibilities for osmotic adjustment and there is an 8 to 10-fold range in salt tolerance of agricultural crops (Ayers and Westcot 1985). Common responses to salt stress are growth inhibition and yield reduction (Asch and Wopereis 2001, Munns 2002). Plant growth is an important indicator for salinity tolerance of agricultural crops (Parida and Das 2005). Thus, knowledge on salinity tolerance of a plant is important when marginal water such as TSE is used for irrigation.

For most crops, the relative salinity tolerance and yield response functions to salinity are known well enough for general salt tolerance guidelines (Ayers and Westcot 1985). Similar to its optimum water requirements, Jatropha's salinity threshold has not been assessed yet. Nevertheless, there is some evidence on its magnitude: Jatropha has been claimed to grow on marginal soil with sandy, gravely and even saline properties (Achten et al. 2008). Dagar et al. (2006) concluded from their study on irrigation with saline water in a semi-arid Monsoon climate, that Jatropha could successfully be grown with irrigation waters having an EC of up to12 dS m^{-1}. In contrast, the FAO classifies Jatropha as salt sensitive having a low salinity tolerance (<4 dS m^{-1}) (FAO Ecocrop 2010).

There is a clear lack of information on the salinity tolerance of mature Jatropha and of Jatropha plants under field conditions. Obviously, this topic needs further research to enable efficient water use and management in Jatropha plantations.

Since the exact salinity threshold of Jatropha was not known, different salinity thresholds / tolerance levels and thus, leaching requirements, were assumed in this study in order to calculate potential matter inputs from TSE irrigation.

Effects of Na+ on soil physical properties

The term soil sodification or alkalization refers to an increased concentration of Na^+ ions on the cation exchange complex of the soil. High concentrations of exchangeable Na^+ implicate a high soil pH and may induce disintegration of soil structure (Oster and Shainberg 2001). Loss of aggregate stability due to clay dispersion, slaking, and soil crusting reduces both infiltration capacity and hydraulic conductivity (Lado und Ben-Hur 2009).

There is a general agreement on the susceptibility of Jatropha to waterlogged soil conditions (e.g. Daey Ouwens et al. 2007). Therefore, the risk of soil sodification (followed by soil structural damage) needs to be evaluated carefully.

Regarding exchangeable Na-concentrations and exchangeable sodium percentage (ESP) overall elevating levels were determined after effluent application (Cromer et al. 1984, Balks et al. 1998). For example, Biggs and Jiang (2009) reported a 20 to 22-fold increase in exchangeable Na in soil irrigated with wastewater, compared to soils irrigated with groundwater. Another study calculated that during a 2-year monitoring period, 2.44 t Na^+ and 4.40 t HCO_3^- ha^{-1} were delivered by TSE using drip irrigation (Gloaguen et al. 2007).

Plant production as a supplemental wastewater treatment: Most important element N

From an environmental point of view, high N-concentrations (especially nitrate-N) of the effluent are of major concern (Pescod 1992, Da Fonseca et al. 2007). Many authors have reported NO_3^- leaching after the irrigation with wastewater (Jordan et al. 1997, Barton et al. 2005, Gloaguen et al. 2007). This represents a potential risk for human health and the ecological balance (i.e eutrophication of surface waters).

TSE application was found to influence N-cycles in the soil (Da Fonseca et al. 2007). Predominantly in long-term studies, the irrigated soils had higher concentrations of total nitrogen (TN) (Friedel et al. 2000, Ramirez-Fuentes et al. 2002). In other studies, TN concentrations in the soil were reduced by mineralization and nitrification processes of soil microorganisms (Da Fonseca et al. 2005). The main reasons for declining N contents were the chemical composition of the effluent and the prevailing N-forms. Furthermore, enhanced microbial activity resulting from ideal conditions (temperature, humidity, O_2), caused considerable nutrient releases from soil organic matter decomposition (Da Fonseca et al. 2007). Short-term changes in soil organic matter turnover, so-called priming effects (Kuzyakov 2002), are known to release or immobilize large amounts of nutrients. This is a common phenomenon in wastewater irrigation and increases its effects on soil N-cycles.

Leal et al. (2010) did not find altered TN contents in sugarcane cropped soils throughout a TSE irrigation period of 16 month. However, there was a considerable increase of NO_3^- in the soil solution, indicating high leaching risks.

The extent of N-leaching depends both on the N-concentrations in the soil and on the predominant N form in the effluent. Nitrification in soils happens within hours, but NH_4^+ ions can be adsorbed to the cation exchange complex of the soil. This may delay microbial processes and decrease N-losses compared to NO_3^-, which is leached easily (Hook and Kardos 1978).
The choice of crops has been found to strongly influence the sustainability of TSE-irrigation (Bouwer and Idelovitch 1987) since plants react differently to a supply of wastewater. Plants can be employed to control the N loss in the soil-plant system by minimizing N leaching (Barton et al. 2005). With regard to N, suitable crops for TSE irrigation should:

(i) have high water and N demands,
(ii) have good potential use, and
(iii) be marketable and economically viable (Da Fonseca et al. 2007).

In general, oil crops have been found to be good catch crops for N from effluent (Al-Jaloud et al. 1996). However, the nutrient requirements of Jatropha are not known, holding the risk of nutrient surplus, leaching, and nutrient deficiency. In this study, the N, P and K requirements of a Jatropha plantation under semi-arid Moroccan climate were estimated based upon information on nutrient contents of different plant tissues. The potential export from biomass harvesting was related to N-P-K input from TSE irrigation assuming a certain irrigation depth. From the N-P-K balance, leaching risks were evaluated.

5 MATERIAL & METHODS

5.1 Study area

The Kingdom of Morocco is situated on the North-western tip of the African continent and occupies a total surface of 750,850 km^2. The country shares borders with Algeria in the East and Mauritania in the South. Morocco's coast is 3,500 km long and lies adjacent to the Mediterranean Sea in the North and the Atlantic Ocean in the West. There are two distinct geographical features dominating the country's diverse landscape: the coastal and inland plains (mostly high plateaus) and four mountain chains of high and medium altitudes that cross the country. These mountain ranges, the Rif Mountains in the North (up to 2,456 m) and the Atlas mountain ranges are separating the Mediterranean and Atlantic plains from the Saharan dessert. The Atlas chains include the Middle Atlas, extending from the Northeast to the Southwest, with altitudes of 2,700 to 3,300 m, the High Atlas further South, peaking in the Mount Toubkal (4,165 m), and the Anti-Atlas (up to 2,500 m) as the most southern barrier. Due to the mountainous relief, the snow-melting lance from the Northern parts of Morocco feeds numerous seasonal watercourses.

Figure 4: Satellite image of Northern and Central Morocco with the four main mountain ranges Rif, High Atlas, Middle Atlas, and Anti Atlas (IMPETUS 2008).

Climate

Morocco's climatic conditions differ considerably between the country's northern part where it is Mediterranean and the semi-arid South. The country's mean annual precipitation is 346 mm. The total annual precipitation in the country's Northwest can reach up to 750 mm a^{-1} while that of the southern part has a total of 150 mm a^{-1} (FAO 2005). Mean annual precipitation is highest with over 1000 mm in the Rif Mountains and the Middle Atlas. The country receives most of its precipitation between October and February. The number of rainy days is around 70 days in the northern parts and at most 30 days in the southern parts.

The spatial variability of the precipitations causes a very uneven distribution of the water resources, which is intensified by seasonal and inter-annual precipitation fluctuations. Usually, a period of several humid years with precipitations above the long-term average is followed by a series of dry years with precipitations below the average. The characteristic alternation of humid and dry cycles leads to considerable yield fluctuation in rain-fed agriculture.

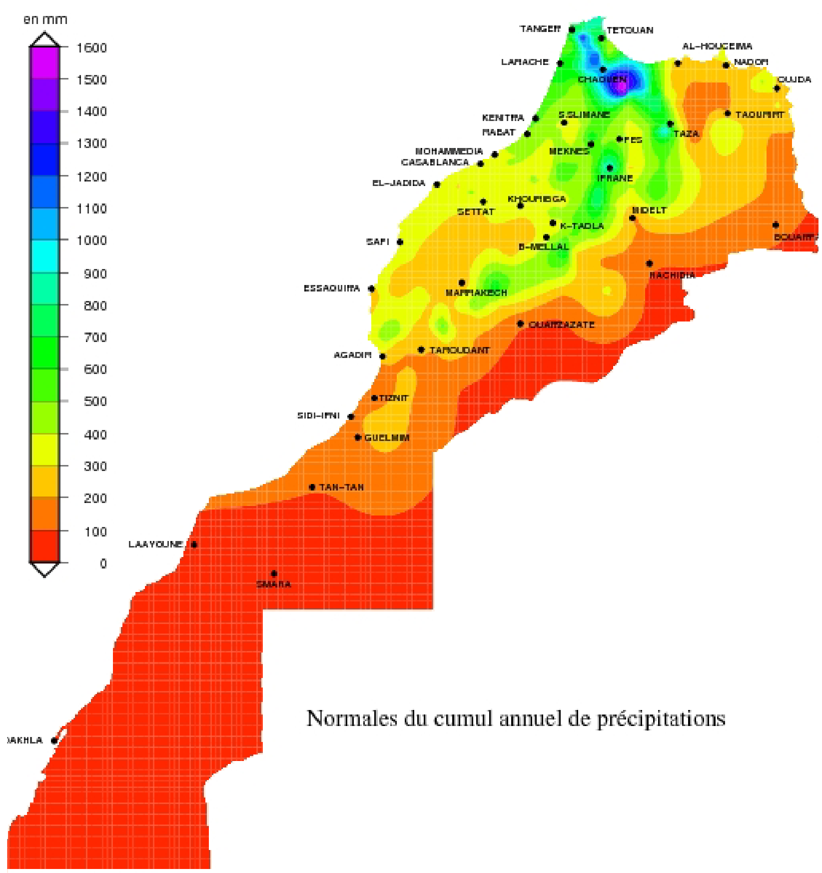

Figure 5: Distribution of the average annual precipitations in Morocco (Source: http://mol.marocmeteo.ma/files/common/images/CLIMAT-DU-MAROC/carte_annuelle_pluie.jpg).

Soils

The soils in the Southern regions of Morocco are predominantly desert soils. Due to low precipitations physical weathering is the prevailing soil formation process. In the Southern regions, where vegetation is scarce, erosion by wind is common. Also secondary salinization takes place. Major soil orders in the Southern regions, which will be discussed here, are Entisols, Aridisols, and dunes, pans or rocklands (USDA 2005) (Figure 6). In the FAO Classification, this corresponds to Calcisols, Regosols, Arenosols and Leptosols (FAO 2003).
The soils are often shallow and have a coarse texture. According to ONEP and FAO (2007), the soils mostly have a good infiltration capacity and hydraulic conductivity.

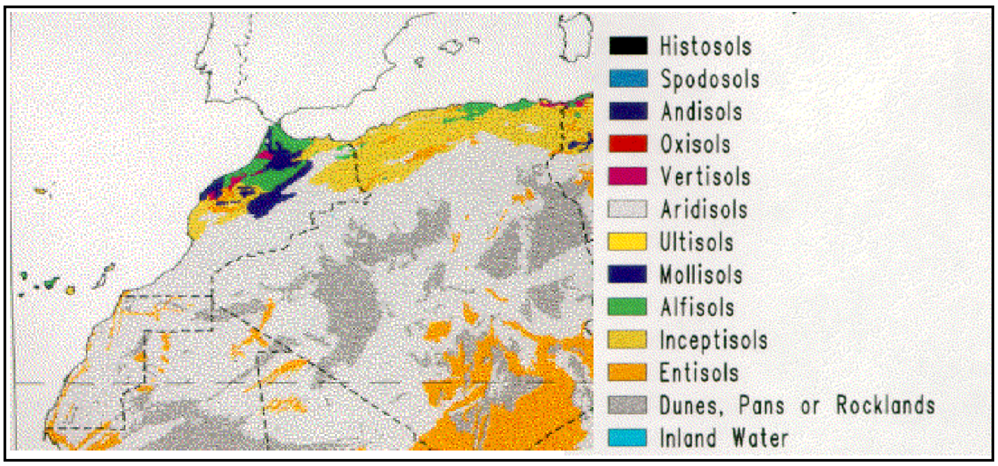

Figure 6: Distribution of the major soil orders in Morocco.

5.2 *Jatropha curcas*

Jatropha, or physic nut, (*Jatropha curcas* L.) is a non-edible oilseed crop with a potential to grow on marginal land. It belongs to the family of *Euphorbiaceae* and is closely related to other important crops such as castor (*Ricinus communis*) and rubber (*Hevea brasiliensi*s). Though it is native to Mexico, Central and South America (USDA 2000), the plant is almost pan-tropic now. It has been planted widely on a small-scale as a multipurpose tree, for fencing, erosion control, as a medicinal plant or for soap and energy production. The established large-scale plantations mainly focus on a commercial exploitation of Jatropha seeds for oil extraction and for the production of bio diesel.

5.2.1 Botany

The deciduous shrub or small tree normally grows to a height of about 5-7 m. Its succulent stem has smooth green bark and develops sturdy branches. When cut, the plant exudes whitish coloured, watery latex. The thick papery leaves measure 8-18 cm, are 4 to 6-lobed, shiny and glabrous. Depending on temperature distribution and water supply, Jatropha can produce leaves all year-round or shed its leaves at the beginning of the dry-season. Leaf senescence may occur due to water shortage or cold spells. The monoecious plant has unisexual terminal inflorescence with a male to female flower ratio from 13:1 to 29:1 (Achten et al. 2008, Raju and Ezradanam 2002). Rare hermaphrodite flowers may occur.

In climates with a distinct dry-season, Jatropha normally flowers and bears fruit once a year, whereas under favourable conditions (water, nutrients, temperatures) two yields or even all year round blooming can be attained. Depending on the environmental conditions and the propagation method, Jatropha starts to fruit after 2 to 3 years. It takes at least another two years to come into full bearing. The productive life of Jatropha is often reported to be 30-50 years (e.g. Debnath and Bisen 2008, Achten et al. 2008). Since yields tend to decrease in older plantations, this remains to be proven (Achten et al. 2008).

The plant has a strong root system. When grown from seedlings, it develops a prominent taproot with strong lateral roots. In sandy soils, the taproot can be double the length of the aerial plant portion. Ye et al. (2009) reported for a plant height of 18-25 cm, a taproot system of 40-50 cm length with 6-10 lateral roots of up to 45 cm.

Jatropha seedlings grow rapidly, have a high biomass production and a high leaf area compared to other tropical deciduous woody species (Achten et al. 2010b). Mean annual increments in height reach up to 50 cm in the first year and above 50 cm in the second year (Ye et al. 2009). An accession trial in India yielded plant heights from 26 cm to 129 cm after the first year in the field and from 73 to 280 cm in the second year (Saikia et al. 2009).

5.2.2 Agronomy

Jatropha's high ecological adaptability (Heller 1996) allows it to be grown under a wide range of environmental conditions. It has been found in altitudes from sea level up to 1,800 m (Foidl et al. 1996). The crop likes warm climate with mean annual temperatures between 19°C and 28°C and a mean daily minimum temperature of the coldest month (T_{min}) above 10°C (Maes et al. 2009b). High temperature extremes can be tolerated, but Jatropha generally fears cold spells and is reported to shed its leaves immediately after frost (Henning 2008). Even though the crop can recover from light frost (Heller 1996), the seed yield decreases and the plant dies after severe frost (Maes et al. 2009b).

Site requirements

In its area of natural distribution, the species commonly grows in tropical savannah and monsoon climates with an annual precipitation minimum of 944 mm (Maes et al. 2009a). Owing to its succulent properties (branches, trunk, roots) and leaf shedding during droughts, Jatropha is well adapted to semi-arid conditions. Nevertheless, more humid environmental conditions have been shown to result in better crop performance (Achten et al. 2008). Besides precipitation depth also rainfall pattern was found to have an influence on crop growth and yield (Daey Ouwens et al. 2007).

Jatropha prefers light to medium soils with adequate drainage (Foidl 1996). Marginal, gravely and stony land with low nutrient supply can also be colonized (Heller 1996). Soil pH should not exceed 9. To support plant growth and root development, the soil depth should be at least 45 cm. Jatropha does not support water logging and damage might occur within days (Achten et al. 2008). Sites with high groundwater tables or heavy clay soils should be avoided.

The crop has low nutrient requirements, but in order to attain high productivity levels, adequate nutrient supply (especially N and P) is necessary (Foidl 1996, Jongschaap et al. 2007). Organic manure, compost and seed cake application have been shown to increase plant growth (Achten et al. 2008). Jatropha responds well to the application of inorganic N and P fertilizers. The optimum application level of fertilizer varies according to plantation age (Patolia et al. 2007) and soil conditions. Also Mycorrhiza was found to enhance nutrient up-take and crop performance.

Propagation and plantation establishment

The crop can both be propagated by generative (direct seeding, pre-cultivated seedlings) and by vegetative (direct planting of cuttings) methods (Heller 1996, Openshaw 2000). Cut branches that sprout readily and grow rapidly enable a fast establishment of hedgerows and plantations (Debnath and Bisen 2008). In contrast to plants emerging from seeds, cuttings do not develop a strong taproot. Hot and humid weather is preferred for good germination of seeds and plant growth (Saikia 2009). If water supply is sufficient, the warm season is best for planting.

Common planting distances are 2 x 2 m (2,500 plants ha^{-1}), 2.5 x 2.5 m (1,600 plants ha^{-1}) and 3 x 3 m (1,111 plants ha^{-1}). In agroforestry systems, wider spacing (5 x 2 m to 6 x 6 m) allows to optimize individual tree yields. Densely planted hedges for soil conservation require a spacing of 15–25 cm (within and between rows) (Openshaw 2000).

Management practices

Trimming hedgerows and pruning plantations is believed to be an important management tool for both yield gain and harvest facilitation (Achten et al. 2008). Since Jatropha produces flowers only terminally, the number of branches significantly controls the number of seeds and thus, the actual yield. Proper pruning induces early ramification and the formation of a bushy appearance with numerous branches. In addition, periodic thinning of the plantations is proposed. Starting from a planting density of 1,600 plants ha^{-1}, the mature stand should be reduced to 400–500 plants ha^{-1} (Achten et al. 2008).

Although Jatropha has been claimed to be pest-resistant, monocultures are likely to face unexpected pest and disease infestations (Shanker and Dhyani 2006). In wild trees, diseases and insect pests are rarely observed (Ye 2009).

5.2.3 Evaluation of a reference climate for Jatropha in Morocco

The use of marginal waters such as TSE represents a potential solution to partly cover the costs of wastewater treatment by simultaneously reducing negative environmental effects of effluent disposal. In Morocco, even though the permanent water supply from wastewater treatment plants would theoretically allow Jatropha production, additional factors, such as the temperature, limit the potential cropping area.

There is a general agreement on Jatropha's area of natural distribution, which is located in Mexico and Central America (e.g. Heller 1996, USDA 2000). In the plant's natural distribution area, the mean daily minimum temperature of the coldest month (T_{min}) is above 10°C. The mean annual temperature ranges from 19-27°C, whereas the mean maximum daily temperature of the warmest month ranges from 27-36 °C (Maes et al. 2009b, numbers rounded). Its tropical origin is the reason for the plants susceptibility to frost.

Due to its lacking frost tolerance, Jatropha seems unsuitable for the climatic conditions of the Northern parts of Morocco and parts of higher altitudes. In contrast to the Mediterranean climate of Morocco's Northern parts, the Southern regions have a semi-arid climate with higher average temperatures. The climatic conditions of Tan-Tan (-11.15 Long [°], 28.45 Lat [°]) (Figure 5) were chosen to represent the reference climate for Southern Morocco. Climate data from the station of Tan-Tan was obtained from the CLIMWAT database (FAO CLIMWAT 2010) (Table 3).

Table 3: Monthly averages of minimum temperature (T_{min}), maximum temperature (T_{max}), air humidity (AH), sunshine duration (Sun), solar radiation (Rad), reference evapotranspiration (ET_0), and rainfall (Rain) in Tan-Tan, Morocco.

Month	T_{min} [°C]	T_{max} [°C]	AH [%]	Wind [km d^{-1}]	Sun [h]	Rad [MJ m^{-2} d^{-1}]	ET_o [mm d^{-1}]	Rain [mm]
January	9.6	21.1	70.0	259	6.2	12.1	2.6	11
February	10.5	21.8	56.0	259	6.8	14.8	3.5	16
March	13.0	23.7	56.0	259	6.8	17.3	4.2	7
April	13.7	23.8	60.0	251	7.1	19.7	4.5	4
May	15.6	24.4	59.0	233	6.9	20.3	4.7	1
June	16.6	25.7	59.0	225	5.6	18.5	4.6	0
July	17.6	27.0	59.0	207	5.2	17.7	4.6	1
August	18.0	29.1	67.0	207	5.9	18.1	4.5	0
September	17.4	28.3	66.0	199	6.2	17.0	4.2	2
October	15.5	27.3	62.0	199	6.8	15.4	3.8	11
November	13.3	25.6	66.0	225	6	12.3	3.1	23
December	9.8	21.5	71.0	251	5.9	11.2	2.5	36
Average	**14.2**	**24.9**	**63.0**	**231**	**6.3**	**16.2**	**3.9**	**112**

5.3 Calculations

5.3.1 Crop evapotranspiration (ET_c)

Knowledge of the water requirements of Jatropha under Southern Morocco's typical climatic conditions is crucial to identify the potential effects of the TSE irrigation on the soil-plant system. The crop evapotranspiration (ET_c) is used to (i) set the magnitude of the surface that could be irrigated with a given volume of TSE, (ii) quantify the matter input delivered by the irrigation waters, and (iii) identify potential agronomic and environmental implications.

The ET_c can be calculated according to the FAO Irrigation and Drainage Paper 56 (Allen et al. 1998). By applying the FAO-Penman-Monteith equation, the so-called reference evapotranspiration (ET_0) of a reference crop in the local climate is established. Effectively, ET_0 is the water requirement of a hypothetical grass crop with defined characteristics such as an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23, under optimal growth conditions (standard conditions). To determine the ET_c of Jatropha, ET_0 has to be multiplied by a plant specific crop coefficient (K_c), which is determined by crop characteristics like resistance to transpiration, crop height, crop roughness, reflection, ground cover, and crop rooting (Allen et al. 1998)(Equ. 1):

$$ET_c = K_c * ET_0 \qquad \textbf{Equ. 1}$$

Where ET_c Crop evapotranspiration [mm],
K_c Crop coefficient,
ET_0 Reference evapotranspiration [mm].

During the cropping season, the plant characteristics and so K_c change constantly. This is accounted for by dividing the cropping season into different growth stages (initial, development, mid-season, and harvest stage), with defined lengths and K_cs.

In cases of a more precise irrigation schedule or soil water modelling, the dual crop coefficient approach can be applied. It splits the single crop coefficient (K_c) into two factors (K_{cb} and K_e), describing separately the differences in evaporation and transpiration between the crop and the reference surface (Allen et al. 1998) (Equ. 2):

$$K_c = K_{cb} + K_e \qquad \textbf{Equ. 2}$$

Where K_c Crop coefficient,
K_{cb} Basal crop coefficient,
K_e Soil evaporation coefficient.

For most agricultural crops, K_c and K_{cb}-values already have been established and can be used for calculating ET_c, provided that climate data is available. For Jatropha there is little information available about potential crop coefficients, so the values had to be estimated.

The FAO-model CROPWAT (Smith 1992) is a convenient tool for the calculation of crop evapotranspiration, basic irrigation requirements (IR), and for irrigation scheduling. Because its handling is straightforward and it is free of charge, CROPWAT 8.0 (Smith 1992) was implemented to calculate the ET_c of Jatropha.

Several input parameters such as meteorological data, soil, and plant characteristics had to be defined (Table 4) to run the computer program. The climate data was obtained from the weather station of Tan-Tan, Morocco, using the CLIMWAT database (FAO CLIMWAT 2010) (Table 3).

Due to the lack of adequate data the necessary plant-specific input parameters (K_c-values according to the growth stages, duration of the growth stages, rooting depth, water depletion fraction, and yield response factor), some assumptions based on an extensive literature research were made:

(i) Sandy soils are common in the Southern regions of Morocco and appropriate to represent marginal soils, so default values from the “UNSODA sand” soil (CROPWAT database) were chosen (Table 5).

(ii) K_c-values and duration of growth stages were modified based on the results of Achten et al. (2010) (K_c of the initial and development stage) and Abou Kheira and Atta (2008) (K_c of the mid-season and late season, planting date, and duration of all growth stages). In case of Achten et al. (2010) the general procedure suggested by Allen et al. (1998) to convert basal crop coefficients into single crop coefficients was applied. Due to the climatic conditions (relatively arid and windy), the K_c's were adjusted.

(iii) The Rooting depth was set to 0.3–1.2 m (Ye et al. 2009)[1].

(iv) The critical depletion fraction was set to 0.4 (Achten et al. 2010b), and

(v) The yield response factor[2] was set to 0.5 (initial stage) and 1 (other stages) (Table 4).

Table 4: Input parameters for calculating the crop evapotranspiration (ET_c) of a potential Jatropha plantation in the reference climate of Southern Morocco with CROPWAT.

Input parameters	Development stage				
	Initial	Development	Mid-season	Late season	*Total*
Duration [d]	43	60	30	75	*208*
K_c-Value	0.6		1.2	0.4	
Rooting depth [m]	0.3		1.2		
Crop height [m]			3.0		
Critical depletion fraction	0.4		0.4	0.4	
Yield response factor	0.5	0.5	1.0	1.0	

Table 5: General soil characteristics of the UNSODA Sand Soil: Total available soil moisture (TAM = FC-WP), maximum infiltration rate (Max. infiltration rate), initial soil moisture depletion (In. soil moisture depletion), and initial available soil moisture (In. available soil moisture) (obtained from CROPWAT 8.0).

TAM [mm m^{-1}]	**Max. infiltration rate** [mm d^{-1}]	**In. soil moisture depletion** [as % TAM]	**In. available soil moisture** [mm m^{-1}]
180	120	20	144

5.3.2 Leaching fractions (LF)

A surplus of water to the ET_c has to be applied in order to remove excessive salt accumulations from the root-zone. The leaching fraction (LF) is the portion of the irrigation water that passes through the entire root zone and percolates below it (Ayers and Westcot 1985) (Equ. 3):

$$LF = \frac{DW}{AW} \qquad \textbf{Equ. 3}$$

Where
LF Leaching fraction,
DW Drainage water [mm],
AW Applied water [mm].

[1] The rooting depth depends on the plant physiology, the type of soil and the water availability (kind of irrigation) (Phocaides 2000). In general, Jatropha is reported to have a strong tap root (e.g. Heller 1996). However, when micro-irrigation with frequent water applications is used, plants tend to develop greater root densities in the upper soil section.

[2] The yield response factor (K_y) describes the reduction in relative yield according to the reduction in ET_c resulting from soil water shortage. In the FAO Irrigation and Drainage Paper 33 (Doorenbos et al. 1979), some crop specific K_y values were presented. Since the K_y of *Jatropha curcas* was not known, average values were chosen to represent the range of potential yield response factors.

The depth of irrigation water necessary to generate a certain LF can be calculated according to equation 4 (Ayers and Westcot 1985):

$$AW = \frac{ET_c}{1 - LF}$$ **Equ. 4**

Where AW Applied water [mm],
ET_c Crop evapotranspiration [mm],
LF Leaching fraction.

In this study, leaching fractions of 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, and 0.5 were assumed.

If the crop salinity tolerance is known, the leaching requirements (LR) can be calculated according to the irrigation water salinity (EC_w) and the soil salinity threshold ($EC_{e\,max}$, determined in the saturation extract) of the specific crop (Ayers and Westcot 1985) (Equ. 5):

$$LR = \frac{EC_w}{EC_{e\max}}$$ **Equ. 5**

Where LR Leaching requirement [mm],
EC_w Electrical conductivity of the irrigation water [dS m^{-1}],
$EC_{e\,max}$ Electrical conductivity of the soil saturation extract at the threshold [dS m^{-1}].

5.3.3 Gross irrigation requirements (IRg)

The gross irrigation requirements (IRg) were calculated according to Phocaides (2000) (Equ. 6):

$$IRg = ((ET_c - P_e)K_r + LR) / E_a$$ **Equ. 6**

Where IRg Gross irrigation requirements [mm],
ET_c Average crop evapotranspiration [mm],
P_e Effective rain [mm],
K_r Reduction factor for crop cover (= ground cover / 0.85),
LR Leaching requirement [mm],
E_a Irrigation efficiency.

For ground cover, a value of 0.8 was taken for trees (Abou Kheira and Atta 2008). The irrigation efficiency was set at 0.8, which is common for micro irrigation systems (Phocaides 2000).

5.3.4 N-P-K requirements

Due to the lack of recommendations for fertilizer application in Jatropha plantations, the minimum nutrient requirements were calculated according to literature data for plant nutrient concentrations in Jatropha. The great majority of the nutrients that have been absorbed by a plant are fixed in its biomass. Only a small portion of it is excreted again by the roots or by other tissues. Therefore, the N, P and K concentrations of different plant organs (cited by Jongschaap et al. 2007) were used to calculate the nutrient stock of Jatropha plants and the potential nutrient exports from fruit harvesting.

5.3.5 N-P-K input from effluent irrigation

The water quality data of Kouraa et al. (2002) from a combined stabilization pond system in Benslimane, Morocco was used to represent a modern type of WWTP (Table 6). In combined systems, pre-treatment is followed by anaerobic, aerated, and facultative treatments. Finally, the water is retained in storage reservoirs. This procedure allows (i) to produce a high effluent water quality and (ii) to schedule irrigations independently from the daily outflow rates of the WWTP (Kouraa et al. 2002).

Table 6: Average values of treated sewage effluent (TSE) and raw sewage effluent (RSE) from a wastewater treatment plant in Benslimane, Morocco (Kouraa et al. 2002).

Constituent	Unit	TSE	RSE
pH		8.4	7.3
EC	(dS m^{-1})	1.4	1.5
TSS	(mg L^{-1})	28.0	200.4
N_{min}	(mg L^{-1})	9.7	39.2
PO_4 P	(mg L^{-1})	2.8	7.9
K^+	(mg L^{-1})	19.5	22.2
Cl^-	(mg L^{-1})	224.0	217.0
Ca^{2+}	(meq L^{-1})	7.5	7.8
Mg^{2+}	(meq L^{-1})	5.2	5.5
Na^+	(mg L^{-1})	102.6	122.3
SAR		2.1	1.8

The nutrient input of N, P and K was calculated using the water quality data of Kouraa et al. (2002). Average concentrations in the effluent were multiplied by the basic irrigation requirements plus LF (Equ. 7).

$$Input\ [mg] = C\ [mg\ L^{-1}] * AW\ [L] \qquad \textbf{Equ. 7}$$

Where C Matter concentration [mg L^{-1}],
AW Applied water [L].

5.3.6 Soil salinity

Due to reasons of simplicity and lack of data for sophisticated modelling, the FAO Irrigation and Drainage Paper 29 was used for calculating the average electrical conductivity of the soil water ($EC_{sw\ average}$) in the root-zone (Ayers and Westcot 1985). The authors proceed on the presumption that in long-term irrigation, the soil salinity approaches some equilibrium concentration, which is controlled by the salinity of the irrigation water (EC_w) and the leaching fraction (LF). The root zone is split into 4 horizontal quarters and it is assumed that the plant extracts 40% of its ET_c from the upper quarter, 30% from the second, 20% from the third and 10% from the fourth quarter (Figure 7).

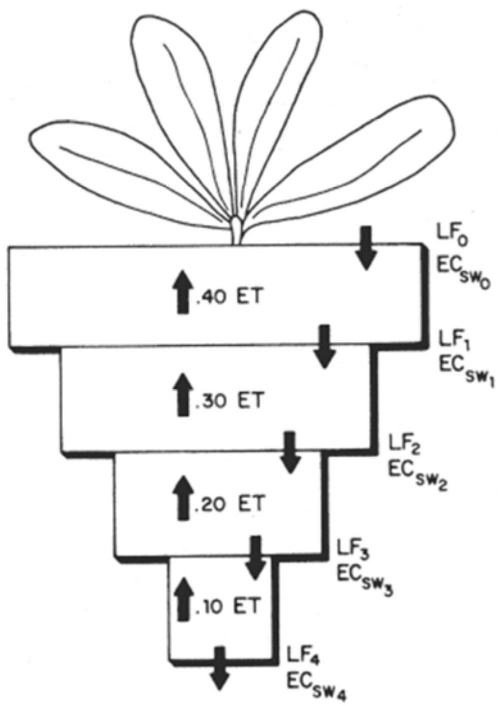

Figure 7: Model for calculating the average soil-water salinity based on a plant water extraction pattern of 40% ET_c from the first, 30% from the second, 20% from the third and 10% from the fourth quarter of the root-zone (Ayers and Westcot 1985).

Based on these findings, the average salinity of the drainage water from the bottom of each quarter (EC_{sw}) can be calculated according to equation 8 (Ayers and Westcot 1985):

$$EC_{sw} = \frac{EC_w}{LF}$$ **Equu. 8**

Where EC_{sw} Soil water salinity [dS m^{-1}],
ET_w Electrical conductivity of the irrigation water [dS m^{-1}],
LF Leaching fraction.

The soil water salinity at the soil surface ($EC_{sw\ 0}$) corresponds to the salinity of the irrigation water (EC_w) because no plant water extraction has taken place. To calculate the average root-zone salinity of the soil water ($EC_{sw\ average}$), the average EC_{sw} of 5 points of the root-zone is determined ($EC_{sw\ 0}$, $EC_{sw\ 1}$, $EC_{sw\ 2}$, $EC_{sw\ 3}$, and $EC_{sw\ 4}$)(Equ. 9):

$$EC_{sw\,average} = \frac{EC_{sw0} + EC_{sw1} + EC_{sw2} + EC_{sw3} + EC_{sw4}}{5} \qquad \textbf{Equ. 9}$$

6 RESULTS

6.1 Water requirements

The crop water requirements include (i) the calculated crop evapotranspiration (ET_c) (6.1.1) and (ii) the leaching requirements (LR) (6.1.2). The basic irrigation requirements (IR) (6.1.3) consider ET_c under local conditions (precipitation, soil), whereas the gross irrigation requirements (IRg) additionally take into account agronomic factors such as ground cover, irrigation efficiency, and leaching requirements.

6.1.1 Crop evapotranspiration (ET_c) and basic irrigation requirements (IR)

For the calculation of the ET_c of Jatropha in Southern Morocco, crop coefficients of 0.6, 1.2 and 0.4 were chosen for initial, mid and late season, respectively (Figure 8).

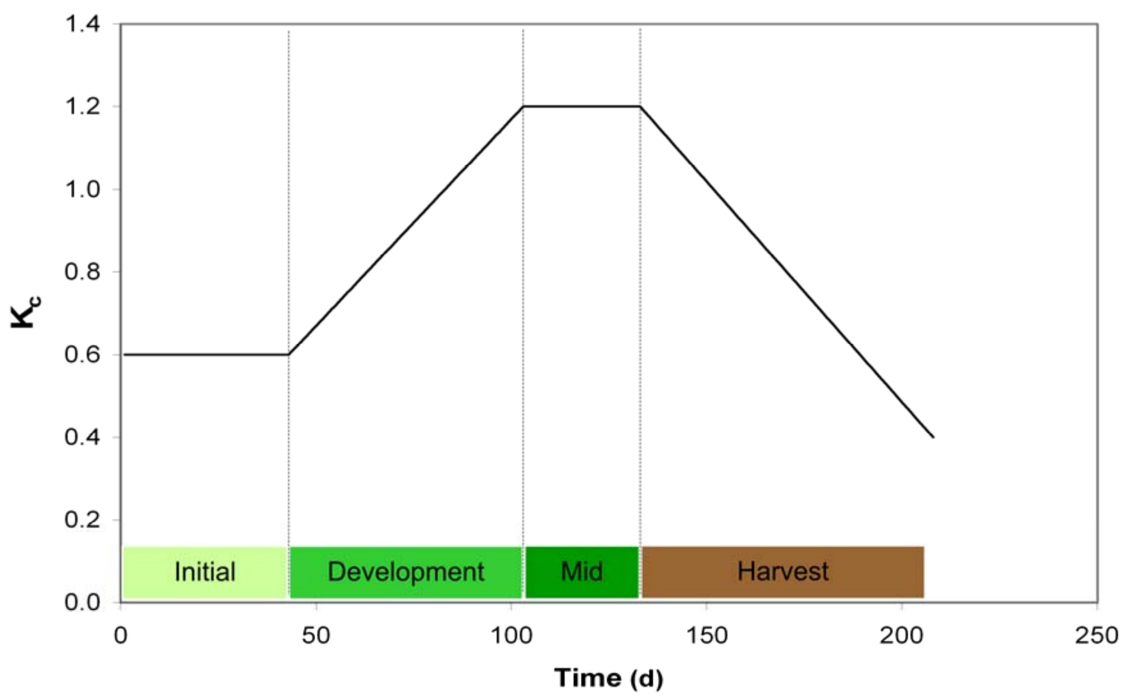

Figure 8: Crop coefficients (K_c) of a potential Jatropha plantation in Morocco during one growing season.

Based on the climate data of Tan-Tan and the K_cs, a total ET_c of 767 mm per growing season (February-August) was calculated. The average daily ET_c ranged from 1.9 mm d^{-1} in the beginning and towards the end of the growing period to 5.5 mm d^{-1} during mid-stage.

Table 7: Crop evapotranspiration (Et_c), effective rain (Eff. Rain), and basic irrigation requirements (IR) of Jatropha in the reference climate during one growing period (February-August).

Month	ET_c [mm]	Eff. rain [mm]	IR [mm]
February	59	16	43
March	83	7	76
April	120	4	116
May	165	1	164
June	156	0	156
July	119	1	118
August	65	0	65
Total	**767**	**29**	**738**

The effective rain totalled 29 mm, which leads to a basic irrigation requirement of 738 mm per cropping season (Table 7). The irrigation requirements per decade were in the range of ~14 mm in February to ~60 mm in May and decreasing constantly to ~13 mm in the end of August.

The monthly basic irrigation requirements were highest in May and June with 165 mm and 156 mm, respectively. Starting with 43 mm in February, the irrigation requirements increased around 40 mm each month until May and decreased again from June on (Figure 9).

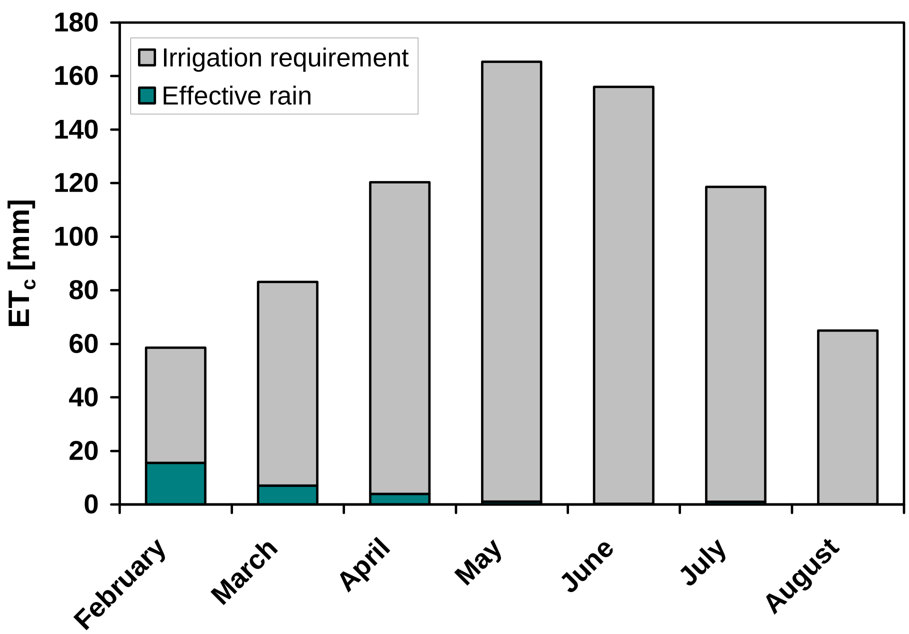

Figure 9: Crop evapotranspiration (ET_c) of a potential Jatropha plantation in Southern Morocco during one growing period: shares of effective rain and basic irrigation requirements.

6.1.2 Leaching requirements (LR)

Depending on the LR, the basic irrigation requirements increased from 738 mm per growing season (without leaching) to 1,476 mm (LF = 0.5) (Table 8).

Table 8: Basic irrigation requirements (IR) consisting of crop evapotranspiration (ET_c) plus leaching fraction (LF) of a potential Jatropha plantation in Southern Morocco.

LF	IR [mm]
0	738
0.05	777
0.10	820
0.15	868
0.20	923
0.25	984
0.30	1,054
0.35	1,135
0.40	1,230
0.45	1,342
0.50	1,476

6.1.3 Gross irrigation requirements (IRg)

The IRg ranged from 868 mm per growing season (without leaching) to 1,329 mm (with a leaching fraction of 50%) (Table 9).

Table 9: Gross irrigation requirements (IRg) of a potential Jatropha plantation during one growing season without leaching and assuming leaching fractions (LF) of 0.05 to 0.5.

	Leaching fraction										
	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
IRg [mm]	868	914	960	1,006	1,053	1,099	1,145	1,191	1,237	1,283	1,329

6.2 Soil salinity

For long-term irrigation, the average root-zone salinity was calculated to be in the range of 9 dS m^{-1} for the lowest leaching fraction (LF = 0.05). In contrast, for the highest LF (0.5) the average root-zone salinity was 2 dS m^{-1} (Table 10).

Table 10: Average soil water salinity (electrical conductivity, EC) at (i) the soil surface ($ECsw_0$), (ii) the bottom of the upper quarter of the root-zone ($ECsw_1$), (iii) the bottom of the second quarter ($ECsw_2$), (iv) the bottom of the third quarter ($ECsw_3$), (v) the bottom of the fourth quarter ($Ecsw_4$) and average root-zone salinity ($ECsw_{average}$) (in dS m^{-1}) resulting from different leaching fractions.

Drainage water salinity		Leaching fraction									
		0.05	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
$ECsw_0$	**[dS m^{-1}]**	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
$ECsw_1$	**[dS m^{-1}]**	2.3	2.2	2.1	2.1	2.0	1.9	1.9	1.8	1.8	1.8
$ECsw_2$	**[dS m^{-1}]**	4.2	3.8	3.5	3.2	2.9	2.7	2.6	2.4	2.3	2.2
$ECsw_3$	**[dS m^{-1}]**	9.7	7.4	6.0	5.0	4.3	3.8	3.4	3.0	2.8	2.5
$ECsw_4$	**[dS m^{-1}]**	28.0	14.0	9.3	7.0	5.6	4.7	4.0	3.5	3.1	2.8
$ECsw_{average}$	**[dS m^{-1}]**	***9.1***	***5.7***	***4.5***	***3.7***	***3.3***	***2.9***	***2.6***	***2.4***	***2.3***	***2.1***

Average soil water salinitiy in the four root-zone compartments ranged from 1.8 dS m^{-1} in the top layers to 28 dS m^{-1} in the bottom layers (Figure 10). The salinity profiles according to the eight different irrigation treatments showed increasing differences concerning the electrical conductivity of the drainage water (EC_{sw}) with increasing depth.

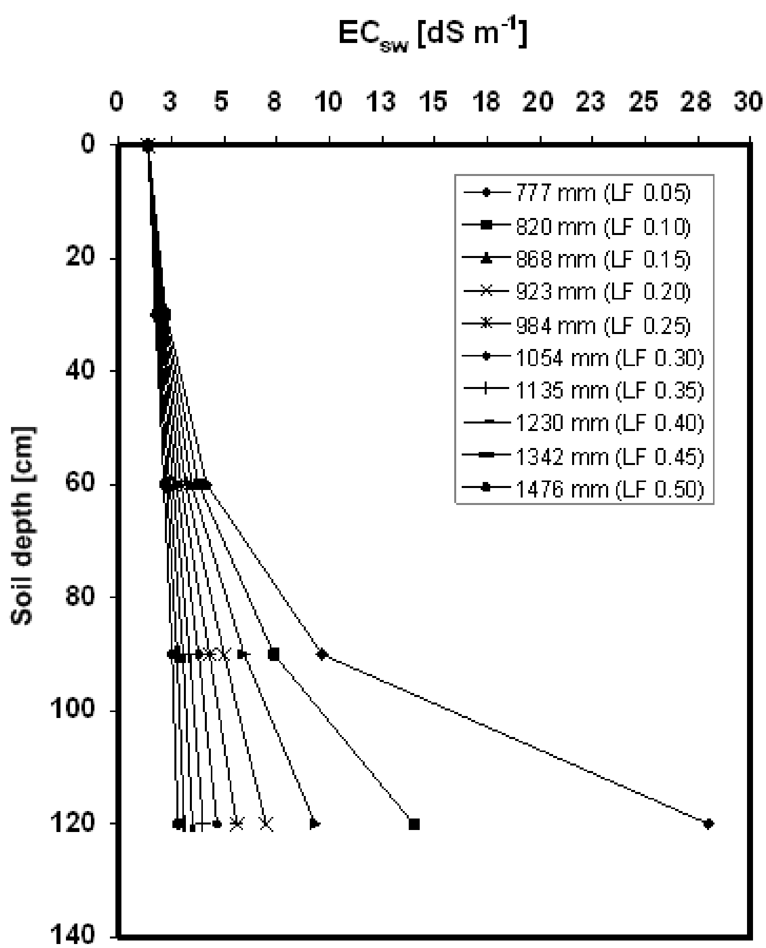

Figure 10: Average EC-values of the drainage water (EC_{sw}) from the four quarters of the root-zone resulting from long-term effluent irrigation with different leaching fractions.

6.3 N-P-K balance

In the following (6.3.1), the term N input from effluent will refer to mineral N (N_{min}) and P will refer to PO_4-P.

6.3.1 N-P-K input

The nutrient delivery from the effluent corresponded to the crop evapotranspiration (Figure 9). Thus, nutrient input was highest in May with an N, P, and K input of 16 kg ha^{-1}, 5 kg ha^{-1}, and 32 kg ha^{-1}, respectively. Until August it decreased constantly to a monthly input of 6 kg N ha^{-1}, 2 kg P ha^{-1}, and 13 kg K ha^{-1} (Figure 11).

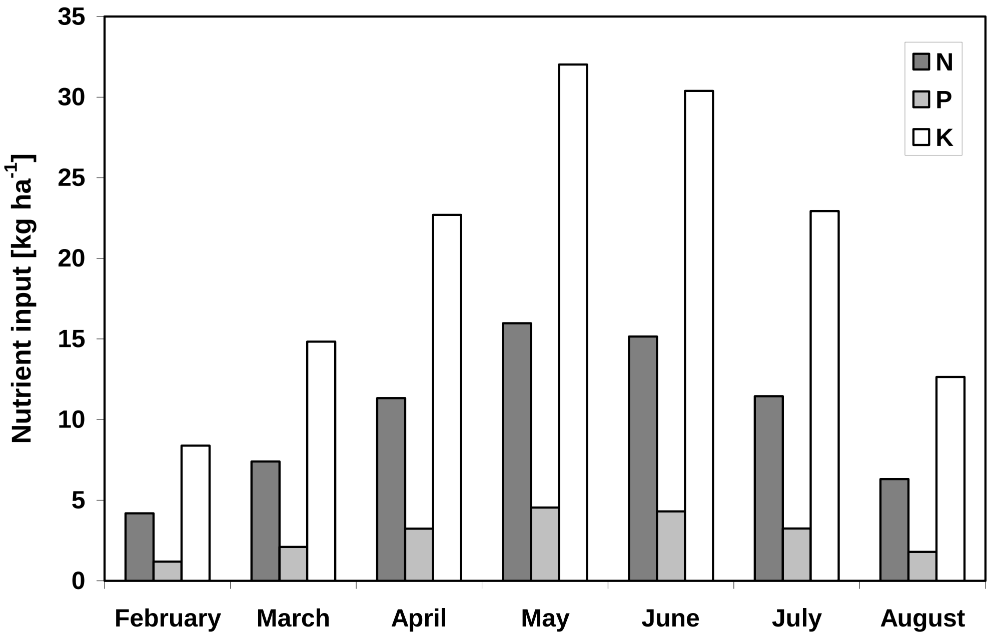

Figure 11: N-P-K input from effluent irrigation (application depth: 738 mm) during one growing period of Jatropha in Morocco.

The nutrient inputs from the effluent increased with irrigation depth. Starting from a total N-P-K input of 72 kg, 20 kg, and 144 kg ha^{-1}, respectively for an irrigation amount satisfying the basic irrigation requirements (ET_c – Eff. rain) , the N-P-K delivery reached 144 kg, 41 kg, and 288 kg ha^{-1} for N-P-K with an irrigation depth of 1.476 mm (LF = 0.5) (Table 11).

Table 11: N-P-K inputs from effluent irrigation at different basic irrigation depths with leaching fractions of 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, and 0.5.

		Irrigation depth [mm]										
Input		738	777	820	868	923	984	1,054	1,135	1,230	1,342	1,476
N	[kg]	72	76	80	84	90	96	103	110	120	131	144
P	[kg]	20	22	23	24	26	27	29	31	34	37	41
K	[kg]	144	152	160	169	180	192	206	221	240	262	288

For the gross irrigation requirements, N-P-K input increased with increasing irrigation depth from 84 kg N, 24 kg P, and 169 kg K per hectare and vegetation period (IRg = 868 mm) to 129 kg N, 37 kg P, and 259 kg K (IRg = 1,329 mm), respectively (Figure 12).

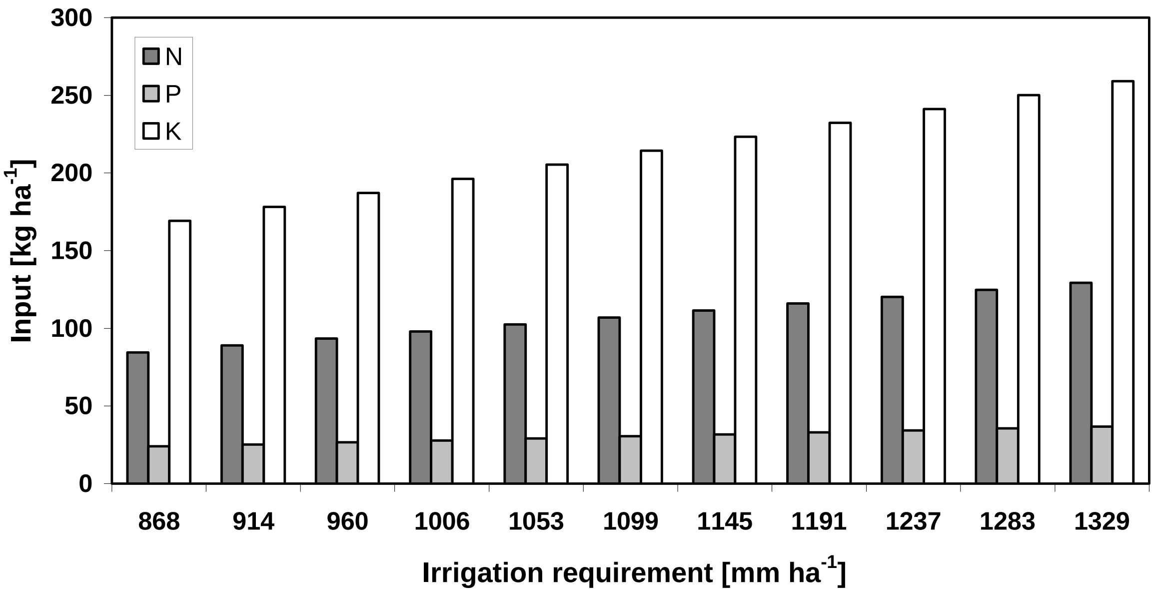

Figure 12: N-P-K-input from effluent irrigation assuming different gross irrigation requirements (without leaching and with leaching fractions of 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, .0.4, 0.45, and 0.5).

6.3.2 N-P-K requirements

According to Jongschaap et al. (2007), the N contents in Jatropha biomass range around 4% in wood and leaves, and around 1.7% in the fruit (consisting of husk and seed). For P, average contents in wood and leaves are around 0.2%, and around 0.5% in the fruit. Average K contents are 3% and 2% in wood / leaves and fruit, respectively (Table 12). Concerning the biomass partitioning, the authors assumed a total dry matter (DM) distribution of 25% of the DM in the wood, 25% in the leaves, and 50% in the fruit.

Table 12: Average concentrations of N, P, and K in Jatropha biomass (Jongschaap et al. 2007, numbers rounded).

	N [kg t^{-1} DM]	P [kg t^{-1} DM]	K [kg t^{-1} DM]
Wood	33	1	29
Leaves	47	3	30
Fruit	17	5	20

Thus, a total dry matter production of 4 t ha^{-1} would consist of approximately 115 kg N, 14 kg P, and 100 kg K in the biomass (Table 13). According to the biomass partitioning suggested by Jongschaap et al. (2007) the share of the fruits[3] is 2 t DM, which is in the range of moderate yields. The corresponding nutrient stocks in the fruits are 34 kg N, 10 kg P, and 40 kg K.

Table 13: N, P, and K stocks in Jatropha plant biomass assuming a total dry matter (DM) production of 4 t (seed yield 1,4 t) and 2,9 t (seed yield 1 t). The total DM partitioning in the biomass was assumed as: 25% in the wood, 25% in the leaves and 50% in the fruit (15% in the husk and 35% seed) (numbers rounded).

	4 t DM			2.9 t DM		
Biomass	**N [kg]**	**P [kg]**	**K [kg]**	**N [kg]**	**P [kg]**	**K [kg]**
Wood	33	1.0	29	24	1.0	21
Leaves	47	3.0	30	34	2.0	21
Fruit						
Husk	5	0.4	25	3	0.2	18
Seed						
Shell	2	0.2	7	2	0.1	5
Kernel	28	9.0	9	20	7.0	7
Total	**115**	**14**	**100**	**82**	**10**	**72**

6.3.3 N-P-K balance

The theoretical ET_c of a mature Jatropha plantation under Southern Moroccan climate was calculated to be 767 mm per growing season. Provided that TSE and rainfall are the only available water sources for irrigation, the basic irrigation requirement is 738 mm. The corresponding amount of TSE would deliver a total amount of 72 kg of N, 20 kg of P, and 144 kg of K per hectare and growing season. The fertilizer value as noted by N, P_2O_5 and K_2O from the total dose of TSE applied would result in 72 kg ha^{-1}, 46 kg ha^{-1}, and 170 kg ha^{-1}, respectively.

If a basic irrigation depth of 1,476 mm per growing season (LF = 0.5) was applied to prevent soil salinization, the corresponding N-P-K amounts would rise up to 144 kg N, 41 kg P, and 288 kg K, respectively (Table 11).

In the previous section (6.3.2) it was calculated that a Jatropha DM production of 4 t ha^{-1} would fix a total amount of 115 kg N, 14 kg P, and 100 kg K in the biomass (Figure 13). Compared to the potential input of N, P, and K from 738 mm of TSE (= ET_c), there would be a lack of N (- 43 kg) and a surplus of P (+ 6 kg) and K (+ 44 kg). The nutrient amount in the TSE equalled the amount of N that was fixed in 2.5 t of Jatropha biomass. For P and K, the amounts in the irrigation water corresponded to the nutrient stocks of about 5.7 t of Jatropha biomass. Only from

[3] In this study, the term fruit is used to describe husk plus seed.

1,135 mm ha^{-1} (LF 0.4) onwards, the amount on N in the water exceeded the N stock in 4 t of biomass.

If only the fruits were harvested and all other biomass was left in the plantation, the nutrient export **per ton DM of fruits** was calculated to be 17 kg N, 5 kg P, and 21 kg K. The N and P amounts that were delivered by 738 mm of TSE equalled the N and P stocks in ~4 t of Jatropha fruits. For K, the delivered quantity was equal to the K stock in ~7 tons of Jatropha fruits.

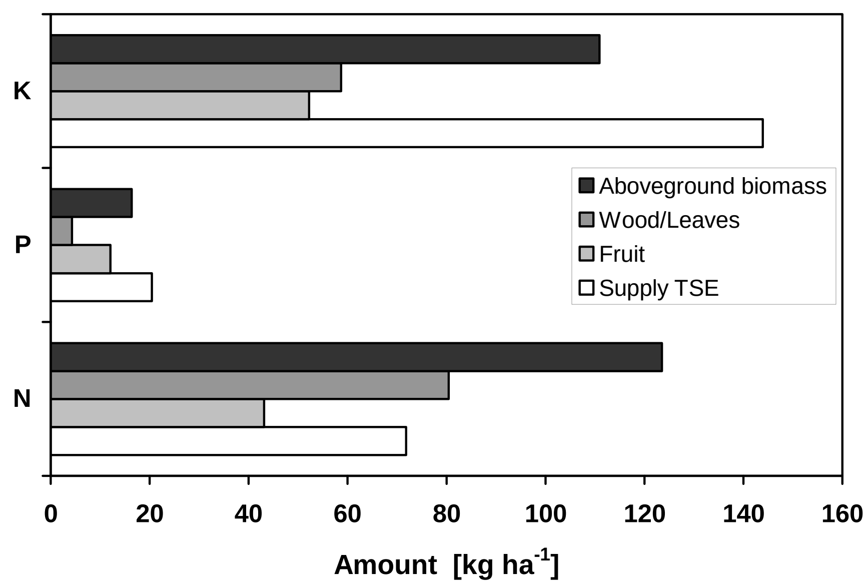

Figure 13: Amount of N, P, and K in Jatropha biomass and N-P-K inputs from TSE irrigation assuming a total dry matter production of 4 t ha^{-1} and an irrigation depth of 738 mm.

7 DISCUSSION

The use of secondary treated sewage effluent is increasingly discussed in Morocco. The production of effluent-irrigated energy crops such as *Jatropha curcas* in close distance to wastewater treatment plants has a potential to secure additional water treatment and thus reduce adverse environmental effects of the effluent disposal. At the same time, the biomass harvested for energetic or material uses can serve as a pay-off for water treatment. To evaluate the sustainability of the system, both (i) the water requirements and (ii) the N-P-K balance of an effluent-irrigated Jatropha plantation in Southern Morocco were determined. The results of the calculations allowed identifying some environmental and agronomic impacts of a treated sewage effluent irrigated Jatropha plantation in a semi-arid climate of Northern Africa.

7.1 Water use and management

The capacity of the wastewater treatment plant in Benslimane is equivalent to the wastewater produced by about 45,000 inhabitants per day (= 45,000 equivalent inhabitant) (Kouraa et al. 2002). An urban inhabitant in Morocco consumes up to 90 L of water per day (see 3.1.1). Assuming a loss of about 10-15% due to leakage of the sewage system and evaporation, the amount of wastewater produced per inhabitant and day can be estimated to be 80 L. Hence, the total capacity of the treatment plant would be 3,600,000 L d^{-1}.

In the context of effluent irrigation, the existence of storage reservoirs is beneficial for both the microbiological water quality and for the general availability of water (WHO 2006). The reservoirs allow water supply according to the crop water requirements since irrigation is not bound to the amount of daily treated outflow.

The size of the Jatropha plantation that could be irrigated with a given amount of effluent depends on the assumed gross irrigation requirements (IRg) which in turn depend on the crop evapotranspiration (ET_c) and the leaching fraction (LF). With an IRg of about 1,084-1,445 mm ha^{-1} and vegetation period (LF 0.2-0.4), the amount of effluent produced by the treatment plant would be sufficient to irrigate between 52 and 69 ha of Jatropha. According to the model of Ayers and Westcot (1985) a LF between 0.2 and 0.4 would allow maintaining average long-term soil salinity in the root zone between 2.4 and 3.7 dS m^{-1}, which is in the range of moderately salt sensitive to moderately salt tolerant crops (Ayers and Westcot 1985).

This numbers only represent approximations of the soil salinity resulting from long-term irrigation and they are intended to provide preliminary guidelines. The actual soil salinity depends on the local conditions and has to be evaluated on-site (Phocaides 2000). Moreover, also short term changes of the root-zone salinity (for example after rainfall events) can adversely affect plant growth.

In this study, the results concerning crop water requirements were based on several assumptions such as Jatropha's K_c or the crop salinity tolerance that still need to be determined. But the results for the crop evapotranspiration go in line with those of several other authors (e.g. Daey Ouwens et al. 2007, Maes et al. 2009b).

However, the calculated ET_c differs considerably from a study on Jatropha plants in Egypt in spite of similar climatic and soil conditions (sandy texture, low organic carbon content) (Abou Kheira and Atta 2008). In the Egyptian study, different irrigation treatments were related to seed yields. The highest yield was obtained by irrigating the trees with 100% ET_0, ($ET_c = ET_0$) implying a K_c of 1 (see Equ. 1). Surprisingly, the gross irrigation requirements during the 7.5 months cropping season were only 178 l per tree (Abou Kheira and Atta 2008).

By extrapolating the individual IRg to an assumed planting density of 2,500 trees ha^{-1}, the authors yielded an annual IRg of only 45 mm ha^{-1}. This is, compared to the annual transpiration water use of 144 mm of 4-year-old, non-irrigated South African plants, very low (Gush and Moodley 2007). It is 70% lower than the pure transpiration water loss measured in South Africa during 9 months and equals only 11% of the ET_c modelled by Jongschaap et al. (2009).

Taking the young age of the trees (2 years) into account, the IRg of mature trees that are fully productive would exceed 45 mm ha^{-1} a^{-1}. Higher water use in later development stages were reported by other authors and ascribed to higher leaf areas (Gush and Moodley 2007) and fruit development (Abou Kheira and Atta 2008).

The study of Gush and Moodley (2007) yielded basal crop coefficients (K_{cb}) of 0.04-0.26 for 4-year-old trees and 0.15-0.76 for 12-year-old trees. However, their K_{cb} differs from the K_{cb} under standard conditions as suggested by Allen et al. 1998. The methodology to calculate K_{cb} used by Gush and Moodley (2007) was to divide the observed daily transpiration values by calculated ET_0-values. This procedure results only in K_{cb} if the sampled crop is growing in large fields under optimal, stress free conditions, with unrestricted water supply (Allen et al. 1998). Because of South Africa's climatic conditions like high temperatures, high VPD, wind and annual precipitations around 550 mm, it is very likely that the plants (occasionally) suffered from water stress. Despite Jatropha's hardiness, its photosynthetic activity and the transpiration rate have been shown to decrease in times of water scarcity (e.g. at 40% plant available water) (Achten et al. 2010b). Hence, the obtained values from rain-fed Jatropha plants reflect its water use under non-standard conditions and are most likely lower than K_{cb}s obtained from Jatropha plants with optimum water supply.

This leads to the conclusion that the K_{cb}-values presented by Gush and Moodley (2007) are a combination of K_{cb} and a water stress coefficient (K_s). Normally, K_s is a supplemental coefficient to calculate the adjusted crop evapotranspiration ($ET_{c\ adj}$), which means ET_c under non-standard conditions (Allen et al. 1998) (Equ. 10):

$$ET_{c\ adj} = (K_s * K_{cb} + K_e) ET_0 \quad \textbf{Equ. 10}$$

Where
$ET_{c\ adj}$ Adjusted crop evapotranspiration [mm d^{-1}],
K_s Water stress coefficient,
K_{cb} Basal crop coefficient,
K_e Soil evapotranspiration coefficient,
ET_0 Reference evapotranspiration [mm d^{-1}].

The K_{cb}'s of the South African study cannot be transferred to Moroccan plantations since the water stress coefficient is unknown.

To calculate the transpiration requirements of a plantation in South Africa, the authors extrapolated individual tree measurements to plantation level (assuming 740 plants ha^{-1}). They yielded transpiration totals of 144 mm a^{-1} and 330 mm a^{-1} for 4- and 12-year-old plantations, respectively (Gush and Moodley 2007).

These values only account for crop transpiration and neglect soil evaporation. To determine the gross irrigation requirement of a TSE-irrigated Jatropha plantation in Morocco, one has to account for supplemental water requirements. These would at least include (i) soil evaporation, (ii) leaching requirements, and (iii) irrigation efficiency. For this reason, the gross irrigation requirements of an effluent irrigated plantation in Morocco are assumed to be a lot higher.

A recent study on biomass production and allocation of Jatropha seedlings under drought stress resulted in K_{cb}-values for immature Jatropha plants ranging from 0.51 to 0.60 (Achten et al. 2010b). These coefficients were obtained under standard conditions and exceed those calculated by Gush and Moodley (2007) considerably. The K_{cb} measured by Achten et al. (2010) indicates the water consumption of young plants in the developmental stage under optimal growth conditions. This study was among the first to deliver adequate data concerning the water requirements of Jatropha. The data was used as a base for the K_c estimations of this study and is expected to provide reasonable results. On the whole, more data is needed to clarify the actual water use of Jatropha.

Jongschaap et al. (2009) used the data of Gush and Moodley (2007) to model the ET_c of the South African plantation. They yielded a total crop evapotranspiration of 405 mm ha^{-1} during one growing season (8.5 months). This is only half the ET_c that was calculated in this study for Jatropha in Morocco. Most probably, the model simulated soil evaporation and crop transpiration under given climatic conditions (652 mm of precipitation), instead of modelling ET_c under standard conditions. If so, the result would represent the water use of Jatropha in a rain-fed production system and not the ET_c under standard conditions with non-restricted water supply.

Of course, Jatropha can produce yield with much less water than the optimum ET_c. This fact was claimed to be the main reason to promote the *Euphorbiaceae* in the beginning of the "Jatropha hype" (e.g. Francis et al. 2005, Achten et al. 2010a). But in case of effluent irrigation, there is an additional interest in nutrient removal from the TSE. The economisation of water is not necessarily the main issue. It is more about finding a sustainable way to purify secondary treated sewage effluent to a reasonable quality with economic benefits for the local population. This is done by producing biomass to meet parts of the local energy demand (e.g. with biofuel and biogas) or to make TSE more valuable for the region by selling the (by-) products of the crop production.

If the biomass harvesting also includes vegetative biomass for biogas production, the focus of the management will shift to a compromise for optimizing both seed and branches / leaf production. But this again depends on the local conditions and will need to be the subject of further research activities.

Concluding it can be stated that the ET_c resulting from this study only represents the potential water requirements of a Jatropha plantation in Southern Morocco under optimum growth conditions. It is based on estimated values and represents a rough magnitude of the actual water requirements. To enable more precise calculations, important factors such as K_c, yield response factor and rooting depth of Jatropha plants under similar site conditions need to be established. Apart from that, regular monitoring of the soil water content (e.g. by using tensiometers) is necessary to clarify the actual water use and thus, the water requirements of Jatropha plants in Southern Morocco and elsewhere.

Besides the absolute irrigation requirements, there are other issues that need to be considered such as matching the availability of water and its demand. The treatment plant provides effluent year-round, whereas the irrigation requirements of a Jatropha plantation in Southern Morocco are only seasonal. The plant is known to shed its leaves in the dry / cold season. Assuming the same vegetation period as the plants in Egypt (Abou Kheira and Atta 2008), there would be a period of 5 month between leaf drop in August and new leaf development in February.

To ensure continuous nutrient removal from the produced TSE, an alternative crop can be grown. Intercropping offers multiple benefits compared to monocultures (Kirby and Potwin 2007). First of all, there is variety in time, space, and structure which can increase the ecological stability of a cropping system. If the crops are combined in the right way, there is a potential of generating positive mutual effects. This can be for instance wind break and shading from the one crop and N-fixation or soil cover to prevent erosion from the other one. Often, mixed cropping is reported to increase biodiversity and decrease pest and diseases infestations by creating niches for useful animals (Bhagwat et al. 2008). Jatropha was claimed to be pest-resistant in the beginning, since wild trees rarely suffer from pest attacks and diseases.

However, in monocultures the need for plant protection measures can increase considerably (Achten et al. 2008).

With the idea of intercropping, several new subjects arise: There are options for temporal and spatial intercropping. In temporal intercropping, the Jatropha trees could serve as a cover crop providing shade and wind break for the second crop in its initial stage. Of course, the harvesting of the Jatropha fruits still needs to be feasible. Further decisions concern the use of the under sown crop / catch crop, which can be harvested or left in the field as mulch (Ripoche et al. 2010).

In spatial intercropping, broader stripes of Jatropha alternating with the second crop probably allow for easier harvesting of both crops, but the efficiency per acreage is generally lower. If intercropping is practiced, also the salinity tolerance of the second crop would influence leaching amounts and timing.

In any case, the second crop should:

(i) Match the local demand (e.g. energetic or material use = energy crops vs. food, fodder or fibre);
(ii) Be suitable for local conditions (climate, soil, TSE irrigation);
(iii) Have a water and nutrient demand which matches the TSE input;
(iv) Should be adequate in terms of pests and diseases (no host for Jatropha pests and vice versa);
(v) Have a salinity tolerance equal or higher to that of Jatropha, and
(vi) Create synergies with the Jatropha production (machinery, equipment, infrastructure).

7.2 Nutrients and fertilization

Through the application of TSE to a Jatropha plantation, a certain amount of nutrients is added to the soil-plant system. This can (i) match the crops nutrient demand, (ii) exceed the crops nutrient demand or (iii) fall below the crops nutrient demand. The benefits of the nutrients in the TSE depend on (i) the nutrient concentration, (ii) the quantities of TSE applied, (iii) the timing of irrigation, and (iv) the type and the target yield of the crop (Janssen et al. 2005).

In order to schedule irrigation and support crop growth, the crop’s water and nutrient requirements need to be known. At present, there are no precise fertilizer recommendations for Jatropha available. The plant is known to respond well to nutrient supply (Achten et al. 2008). In an extensive report on current Jatropha activities worldwide, the authors pointed out that fertilization was practiced regularly in 67% of the surveyed projects (n=90) (GEXSI LLP 2008).

Patolia et al. (2007) conducted a fertilizer trial on marginal soils with different levels of mineral N and P fertilization. During a study period of two years, the plants showed best growth results with a N level of 30 kg ha^{-1} and a P level of 10 kg P_2O_5 ha^{-1}in the first year and 45 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1} in the second year. The highest yields were obtained by applying 60 kg of N and 30 kg of P_2O_5. However, these results stem from a plantation in the development stage. In a mature plantation, the only nutrient export is from harvesting the fruit (provided that pruning material is left in the plantation and erosion and leaching is being neglected).

Jatropha is a perennial crop that invests a fraction of its carbohydrates into the wooden standing biomass. This fraction decreases over time (Jongschaap et al. 2007). As long as regular pruning is performed, the seasonal nutrient requirement is only needed for the formation of new branches, leaves, flowers, and fruits. The main biomass which is produced is on the one hand fruits (consisting of husks and seeds) and on the other hand vegetative biomass (branches and leaves) (Achten et al. 2008). When comparing the nutrient inputs from TSE and the nutrient stocks in Jatropha biomass, two different management scenarios have to be distinguished: (i) fruit harvesting only and (ii) fruit harvesting and energetic use of the by-products (e.g. pruning material).

If senescent material such as leaves and pruned branches are left in the field as mulch, they are decomposed. During decomposition the nutrients are slowly released and become available to the plant again. Aside from the positive effects of closed nutrient cycles, the application of mulch has also shown to reduce soil water losses from evaporation and increase soil organic carbon (Cadavid et al. 1998).

The advantages of harvesting only the fruits are minimum nutrient exports and maximum carbon stocks in the plantation even though the plantation's potential for energetic use wouldn't be exploited fully. In the future, also the potential for carbon sequestration in both the plant biomass and in the soil could provide supplemental gains in the context of CDM projects (WBGU 2009).

In case of further exploitation of the by-products (e.g. use of pruning material and seed cake for anaerobic fermentation) the recirculation of the digestate from biogas production to the plantation would reintroduce most of the nutrients (and to a much lower degree the organic carbon). But the calculation of the second scenario is beyond the scope of this work and will not be discussed here.

By satisfying the calculated basic irrigation requirements of a Jatropha plantation in Southern Morocco, the TSE would deliver a total input of 72 kg mineral N, 20 kg Phosphate-P, and 144 kg of K ha^{-1} during one vegetation period. Achten et al. (2008) estimated that harvesting the equivalent amount of fruit to yield 1 t of seeds results in a removal of about 14–34 kg N, 0.7–7 kg P, and 14–32 kg K. The results obtained in this study (25 kg N, 7 kg P, and 30 kg K) go in line with the calculations of Achten et al. (2008). If the vegetative biomass is left in the plantation, fertilization has to compensate at least for the nutrient exports of the harvested fruits. Theoretically, the amount of nutrients delivered by the equivalent amount of TSE satisfying the

ET_c corresponds to the nutrient stock in the amount of Jatropha fruit that has to be harvested to yield about 3 t of seeds.

A seed yield of 3 t ha^{-1} (DM) is very ambitious given that Jatropha is still a non-domesticated plant. According to other authors (e.g. Jongschaap et al. 2007, Achten et al. 2008) the reports on yields vary between 0.2 and 7 t ha^{-1}. Often it is unclear, if the weight is dry or fresh, and if is that of the whole fruit, the seed or just the kernel (Jongschaap et al. 2007).

In this study, the calculations of the nutrient stock of Jatropha biomass were based on a few sources with clear variations. For concrete calculations, the nutrient contents of different Jatropha organs have to be revaluated.

In terms of figures, it has been shown that the nutrient contents in the effluent are sufficient to cover the nutrient export of a seed yield of ~3 t (corresponding to 4 t of fruits). The question is: How much of the water's nutrient load could actually be absorbed by the Jatropha plants?

The nutrients delivered by the effluent can be subject to the following processes:

(i) uptake by the crop and removal from the field via the harvested crop components (here: the Jatropha fruits),

(ii) uptake and excretion via the roots of the crop,

(iii) microbial immobilization and accumulation in the soil, or

(iv) loss through erosion, volatilization, and leaching (Janssen et al. 2005).

This means that the nutrients are either exported via harvest and losses, or they remain in the soil because of root excretion, immobilization, and accumulation.

According to Janssen et al. (2005) the nutrient value of TSE for crops can be estimated from soil fertility and use efficiency of the added nutrients. The so-called nutrient recovery efficiency is an indicator for the nutrient uptake of a crop. It is the ration between the quantity of the nutrients stocked in the plant biomass and the applied nutrient dose. Janssen et al. (2005) cited theoretical maximum recovery efficiencies for cereals of 80, 85 and 70% for N, P, and K, respectively.

The nutrients have different characteristics concerning their availability and accumulation. For N, losses by leaching and volatilization can be considerable, whereas accumulation is negligible. Elevated concentrations of mineral N, especially NO_3-N, have been found in the soil solution after TSE irrigation (Johns and McConchie 1994, Speir et al. 1999, Barton et al. 2005). Leal et al. (2010) reported N concentrations of up to 388 mg L^{-1} in the soil solution of TSE irrigated sugarcane throughout the growing season. However, the corresponding N concentrations in the effluent were 32 mg L^{-1}. In contrast, the TSE considered in this study has N_{min} concentrations of only 10 mg L^{-1}. Regarding the relatively low N contents of the TSE and assuming irrigation according to the ET_c, no great leaching risks are expected in this study.

In contrast, for P, leaching is not important but accumulation may be very high. This depends very much on the soil pH, which is can be slightly elevated due to effluent irrigation (Da Fonseca et al. 2007). This holds especially true for light, carbonate-free soils having a pH <7 (Gisi et al. 1997). Heavy soils with an adequate cation exchange capacity are normally less affected.

For K, both leaching and accumulation is found, but since it is easy to mobilize again, it can be considered as plant available (Janssen et al. 2005).

Apart from the total amount of nutrients that is added to the soil-plant system, also the general nutrient availability plays an important role. It is controlled by several factors such as soil pH and C/N ratio. Besides the discussed macronutrients, also micronutrients are essential for plant growth. In order to avoid nutrient imbalances or toxicities resulting from certain contraries (e.g. Boron, salt, heavy metals) in the effluent, the health and nutrient status of the plants has to be monitored regularly to avoid crop failure and allow continuous effluent treatment.

For example Na, which is usually the most abundant cation in TSE, is not considered as a plant nutrient. It is known to provoke the displacement of Ca, which in turn can cause Ca deficiencies in plants. Other practical issues related to effluent irrigation are the general problems of emitter clogging due to the high amounts of suspended solids in the effluent or to carbonate formation. However, these topics will not be addressed here. They have been discussed elsewhere (e.g. Pescod 1992, Pedrero et al. 2010).

In a combined plant production / effluent treatment system, the focus is determined by various economic and ecologic factors (see also Figure 3). If the protection of the environment is a priority, the main objective will be to avoid excessive nutrient leaching (especially N and P). By contrast, when focusing more on (short term) economic effects, the profit contribution in plant production is of principal interest. A sustainable solution has to take into account both sides. This means that in a sustainable plant production / effluent treatment system the main objective should be to minimize nutrient losses by optimizing plant production. This can only be obtained by a sound plantation management based on regular monitoring of the water quality and the soil-plant system.

Constant monitoring of the water quality is crucial because of the linked households' seasonal variation in water use, which leads to fluctuating matter concentrations in the effluent (WHO 2006, ONEP / FAO 2007). These changes need to be considered in management plans and schedules. In addition, the water quality can vary considerably due to discontinuities in the treatment procedure caused by highly polluted industrial effluents or mismanagement.

In crop production systems, the nutrient recovery efficiency strongly depends on the management (e.g. irrigation): If the nutrients are at close distances to the roots, they can easily be taken up by the crop (Janssen et al. 2005).

In TSE irrigation, water and nutrients are delivered simultaneously (= fertigation). Micro irrigation systems offer various advantages through the efficient application of water and fertilizer. In addition, they are able to reduce adverse effects of TSE on humans and the environment (WHO 2006). Drip irrigation and sub-surface drip irrigation can considerably reduce the reuse criteria. When using sub-surface drip irrigation the soil acts as additional filter and there is hardly any contact between TSE and crop or workers above the soil surface (Oron et al. 1999). Even though the investment costs in micro-irrigation systems are higher compared to regular surface irrigation systems, it can reduce the need for expensive wastewater treatment, enhance efficient water use and decrease environmental pollution (Heidarpour et al. 2007). Due to precise application rates and equal distribution of the effluent, leaching losses and thus, pollution of the groundwater can be minimized. In Morocco, the installation of drip irrigation systems is currently subsidised (AHT Group AG 2009).

However, if excess water is applied (e.g. to control salinity built-up) the risk of nutrient leaching rises (Barton et al. 2005). If TSE is used for leaching, the comprised nutrients are flushed representing a potential risk for groundwater contamination or surface water pollution. The extent and the timing of leaching processes have to be matched to the local conditions and are a question of site specific management.

7.3 Soil salinity and sodicity

The concentrations of total dissolved solids (TDS) and the proportion of Na in irrigation water are key factors for classifying water as suitable, problematic or unsuitable. Irrigation with TSE often leads to elevated salt and Na concentrations in the soil (Pescod 1992, Da Fonseca et al. 2007). Soil salinity and sodicity may have negative effects on crop growth and yield (Ayers and Westcot 1985, Kjine et al. 1998) since they adversely affect water availability and soil structure.

The parameters that have to be taken into consideration when assessing a water's suitability for irrigation are (i) total salinity, (ii) crop response to salinity, (iii) sodium hazard, and (iv) toxicity problems and nutrient imbalances (Phocaides 2000).

Total salinity and crop response to salinity

The lower limit of EC_e of a saline soil is set at 4 dS m^{-1}. In fact, sensitive plants (e.g. beans, citrus) are affected at about half this electrical conductivity and more tolerant ones (barley, sugar beet) at about twice this EC (Ayers and Westcot 1985). The factors influencing the crop salinity tolerance are (i) plant species, (ii) development stage, and both (iii) nutrient and (iv) hydraulic status (Phocaides 2000).

The FAO (FAO Ecocrop 2010) classifies Jatropha as a moderately salt tolerant crop requiring soil salinity levels below 4 dS m^{-1}. In contrast, field trial on irrigation of perennials with saline water in India yielded different results. The authors concluded that Jatropha could be grown successfully using irrigation water with an EC_w of up to 12 dS m^{-1} with average root-zone salinities >3 dS m^{-1} (soil depth 0-60 cm).

With an EC_w of 1.4 dS m^{-1}, the TSE considered in this study is only slightly saline. Following the criteria of Ayers and Westcot (1985), there would be a slight to moderate restriction on use because of the water's EC that ranges between 0.7 and 3 dS m^{-1}. Regarding the high concentrations of Ca and Mg in the irrigation water, the salinity risk will be less severe.

As mentioned before, the salinity tolerance of Jatropha has not been assessed, yet. Some results have been published supplying data on the salinity tolerance of Jatropha seedlings. Gao et al. (2008) reported from a germination experiment that Jatropha seedlings did not show significant growth reduction at NaCl concentrations of 50 mmol. The seedlings even tolerated NaCl concentrations of up to 150 mmol. Higher concentrations caused toxic effects. During the experiment increased levels of antioxidant enzymes such as superoxide dismutase, peroxidase and catalase indicated Jatropha's tolerance capacity to protect its cells from oxidative damage. The enzyme activities varied according to NaCl concentrations and plant tissue (Gao et al. 2008).

The salinity tolerance of a crop strongly controls the leaching requirements in irrigation. This, in turn, influences the gross irrigation requirements and the amount of nutrients that is delivered by the effluent. The different estimations of Jatropha's salinity tolerance would in practice provoke different gross irrigation requirements and thus, different nutrient delivery scenarios. To avoid excessive nutrient leaching, the salinity tolerance of Jatropha needs to be identified. Following the calculations in 6.2, the required leaching fraction for a long-term irrigation project would be at least 20% in order to maintain the average salinity in the root-zone below 4 dS m^{-1}.

With leaching fractions in this range, it is important to install drainage systems to avoid water logging and secondary salinization. Appropriate drainage facilities should be integrated in early planning phases of TSE irrigation projects (Pescod 1992).

Sodicity hazard

Other problems when using TSE irrigation for Jatropha production might be the damage to the soil structure due to soil sodicity. Jatropha is susceptible to water logging and will not thrive in collapsed soils, especially without drainage facilities (Jongschaap et al. 2007).

In addition, sodicity and alkali stress have been shown to impede growth of Jatropha seedlings (Kumar et al. 2008). Na^+ is usually the most abundant cation in TSE. Due to its adverse effects on the soil's physical and chemical properties and plant growth, Na is a problematic and undesired element in irrigation water. Generally, elevated levels of soluble Na concentrations and exchangeable sodium percentage (ESP) have been observed in effluent-irrigated soils (Stewart et al. 1990, Pescod 1992, Biggs and Jiang 2009). The Na accumulations appeared mainly in the topsoil to an expense of Mg and Ca. The magnitude of the changes depended on local conditions such as soil type, crop, climate and quantity / quality of the applied wastewater (Da Fonseca et al. 2007).

The physical and mechanical properties of soil (permeability, dispersion of particles, stability of aggregates, and soil structure) are very sensitive to exchangeable ions (primarily Ca^{2+}, Mg^{2+} and Na^{+}) present in the irrigation water. Na^{+} is adsorbed to the cation exchange complex while Mg^{2+} and Ca^{2+} are released to the liquid phase (monovalent-divalent exchange). Jalali et al. (2008) conducted leaching experiments on calcareous soils from long-term wastewater irrigated fields in Iran. They observed that the highest concentrations of Mg^{2+} and Ca^{2+} in the leachate occurred simultaneously with the lowest concentrations of Na^{+}. As a result, the ESP of both soils increased. During a leaching procedure with good quality water, both soils showed a considerable decrease in their outflow rates. This indicates soil structural damage, resulting in reduced permeability and soil hydraulic conductivity. If concentrations of EC and SAR are in an appropriate ratio, soil physical deterioration (= loss of aggregate stability) will not occur. This is the case for the effluent considered in this study. Due to the high concentrations of Ca^{+} and Mg^{2+}, the SAR and EC are in an appropriate ratio to avoid infiltration problems (Ayers and Westcot 1985).

However, when the water quality changes (precipitation, change in irrigation or leaching water) there is a risk of seal formation and breakdown of soil structure, resulting in reduced permeability and decreasing soil hydraulic conductivity. For Jatropha, this might be important in the off-season, where leaves are shed and the good quality water precipitates in erratic but strong rainfall events. The point at which Na-driven physical changes in the soil occur is influenced by soil texture, mineralogy, and organic matter content. Before the beginning of TSE irrigation pre-feasibility studies are necessary to evaluate water quality in soils, their discharge to groundwater and the risk of soil structural deterioration.

Depending on the soil texture and pore size distribution, increased amounts of total suspended solids (TSS) have also shown to reduce soil hydraulic conductivity by plugging the pores (Lado et al. 2005).)

In general, soils prone to structure degradation should be carefully evaluated before irrigated with TSE. Otherwise, TSE-irrigation could result in seal formation and increased run-off, which in turn would enhance soil loss and reduce local soil- and groundwater recharge (Lado et al. 2005).

8 CONCLUSIONS & OUTLOOK

In this study, the water requirements of a Jatropha plantation in Southern Morocco irrigated with treated sewage effluent were identified. Depending on the leaching fraction, a surface of 52-69 ha theoretically could be irrigated during one vegetation period. The irrigation water makes up for the water loss through crop evapotranspiration and delivers nutrients exported by approximately 4 t of fruits (seed yield of ~3 t). However, Jatropha is reported to shed its leaves in the winter season, implicating to a potential vegetation period for Jatropha in Southern Morocco from February to September. Hence, nutrient removal is not continuing during 5 months. This issue can be addressed by intercropping Jatropha with other crops, which is also useful to increase the stability of the cropping system. Suitable intercropping options have to be evaluated for future projects.

The crop evapotranspiration of 767 mm calculated in this study was based on estimated values obtained from literature research. These parameters (e.g crop coefficients, vegetation period for crop evapotranspiration, salinity threshold for leaching requirements) have to be established in the near future to enable more precise calculations.

Depending on the leaching fraction, the risk for nutrient leaching was assumed to be relatively low in this study. In spite of this, regular monitoring is a crucial issue since effluent quality in low input systems is subject to frequent variations. Additionally, it has to be stated that the nutrient concentrations (especially N) of the TSE water in this study were low compared to average concentrations worldwide (Da Fonseca et al. 2007).

Certainly, plant production as a supplemental wastewater treatment represents a sound ecological method for wastewater disposal (Toze 2006). The extent of the nutrient filtering depends on the nutrient recovery of the crop and above all on the management of the local system. In case of effluent irrigated Jatropha plantations, both topics need to be subject to further research.

In the global context, it is clear that effluent reuse in agriculture will increase in water scarce countries in the near future. This is necessary to release precious freshwater resources for the supply of drinking water in the ever-growing urban areas and for unrestricted irrigation.

The cultivation of energy crops such as Jatropha has the advantage of lower microbiological quality requirements of the effluent compared to those in food production (WHO 2006). Especially in water scarce countries like Morocco, micro irrigation is favourable in effluent irrigated agriculture, because of both hygienic issues and general water saving characteristics.

Concerning the economics of wastewater treatment with perennial energy crops such as Jatropha, carbon sequestration is another topic that needs to be researched to allow the categorisation of plantations in the context of Clean Development Mechanism (CDM) projects (WBGU 2009).

After all, the competitiveness and sustainability of Jatropha cultivation compared to other energy crops depends on more than the water and nutrient requirements. It is strongly controlled by factors like availability of harvest technique and harvest costs, the need for plant protection measures and suitability of the crop to the local conditions. As mentioned before Jatropha is still a wild plant and reliable yield prognoses remain difficult. Currently, seed harvesting is done mostly manually (GEXSI LLP 2008), which leads to an increase in production costs in medium to high income countries. Nevertheless, in case of using the by-products (pruning material, husks, press-cake) alternative production systems have a potential to successfully combine biomass production and supplemental effluent treatment.

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Pictures

Figure 5: Distribution of the average annual precipitations in Morocco:

http://mol.marocmeteo.ma/files/common/images/CLIMAT-DU-MAROC/carte_annuelle_pluie.jpg)

ACKNOWLEDGEMENTS

I am grateful for the inspiring support of Prof. Dr. Folkard Asch, who always gave me great advice.

Many thanks go to Prof. Georg Cadisch for his interesting and though-provoking impulses.

I highly appreciate the ground-connecting comments of Dr. Carsten Marohn, who was never too busy to answer my clouded questions.

I enjoy the valuable inspiration and help of my colleagues from IfaS: Thanks for making me quit my endless student life!

Thanks to Loredana Kraushaar for her linguistic lessons.

And finally, thanks to my family and especially to Michael Ben-Lila who enlightened my semi-arid days full of word(s), numbers, and articles.

Do your practice and all will come.

Sri K. Pattabhi Jois

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