Improvement of Detention Ponds with Respect to Salinity

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Kurzfassung

Dränteiche dienen dem Wasserrückhalt, der Reinigung landwirtschaftlicher Dränabflüsse und bieten eine Alternative für die Bereitstellung von Beregnungswasser. Hydraulische Probleme wie Totzonen, Kurzschluss-Strömungen, Verwirbelungen und, besonders in ariden und semiariden Gebieten hohe Salinitäten sowie Verdunstungsverluste sind Herausforderungen für ihre Anwendbarkeit. Im Rahmen dieser Arbeit wurde das Potenzial von Wasserlinsen *(Lemnaceae*) zur Stoffentnahme bei hohen Salzgehalten untersucht sowie Methoden zur Optimierung von Dränteichen getestet.

Klimakammerversuche sowie Freilandexperimente unter humiden Bedingungen zeigten eine Wachstumsbegrenzung mit steigender Salinität, jedoch ein zunehmendes Wachstum bis 1.6 g/l. Die Salz - Entnahme beruht auf der Kinetik 1. Ordnung und betrug 0.5 - 12 %, in Abhängigkeit von der Salinität sowie der Biomasse. K^+, Mg^{+2}, Na^+, Cl^-, und NH_4^+ wurden unabhängig von der Salzkonzentration aufgenommen, Die NO_3^- und Ca^{+2} Aufnahme verringerte sich. Die Verdunstung wurde zu 25 % gesenkt.

Numerische Simulationen mit TELEMAC 2D zeigten, dass sich die Anordnung der Wassereinleitung in den Dränteich, die turbulente Viskosität, sowie hohe Dränzuflüsse sowohl auf die Strömung als auch auf den Stoffabbau auswirkten. Die zusätzliche Anordnung von künstlichen Barrieren verbesserte die Effektivität, wobei für den untersuchten Dränteich vier Barrieren mit ca. 70 % der Breite des Dränteiches am effektivsten waren.

Die Ergebnisse bieten Lösungen für eine Nutzung in arid/ semi-ariden Gebieten an. Eine Biomasseproduktion der *Lemnaceae* von größer als 260 g/m^2, eine regelmäßige Ernte sowie die individuelle Anpassung der Dränteiche mit Hilfe von Simulationsmodellen werden dabei empfohlen.

Abstract

Detention ponds can be used for storage, treatment and reuse of agricultural drainage water as one alternative for freshwater in irrigation. Generally, ponds' hydraulic problems such as dead zones, short - circuiting and swirling and, particularly, water salinity and scarcity in arid/semi - arid areas are challenges facing the ponds' applicability. The purpose of this work is to investigate the potential of duckweeds (*Lemnaceae*) for salt and nutrient uptake under different salinities as well as the methods for optimization of detention ponds.

Investigations under controlled climate conditions and under natural humid climate conditions with different water salinities showed a significant growth inhibition by salinity, but with a promoted growth up to 1.6 g/l. Salt - removal was a first - order kinetic and ranged from 0.5 - 12 % per day dependent on water salinity and duckweeds' biomass. K^+, Mg^{+2}, Na^+, Cl^-, and NH_4^+ have been removed independent on water salinity, but NO_3^- and Ca^{+2} removal decreased significantly by salinity increase. Duckweeds saved up to 25 % of the water volume lost by evaporation.

Numerical simulations of an actual detention pond in the State of Brandenburg, Germany with the modelling system TELEMAC 2D showed that the pond inlet design, turbulent viscosity, and flood influenced both, the flow and transport processes. Design modification by baffles improved the performance. Four baffles of 70 % of pond width achieved the best performance.

In conclusion, detention ponds can be, generally, more effective, sustainable and, particularly, applicable in arid/semi - arid areas, if duckweeds' species are cultivated with intensity higher than 260 g/m^2, harvesting of duckweeds is done regularly, and numerical simulation of every pond is undertaken individually.

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Acronyms and Abbreviations

BOD_5	[mg/l]	Biological oxygen demand
Ca	[mg/l]	Calcium
Cd	[mg/l]	Cadmium
Cl	[mg/l]	Chloride
C_r	[-]	Courante number
e	[-]	Hydraulic efficiency of a detention pond
EC	[dS/cm]	Electrical conductivity
EC_X	[mg/l]	NaCl concentration dissolved in test medium that results in X% growth reduction in *lemna* test
I	[-]	Index of short circuiting
I_b	[-]	Inhibition percent of *Lemna* growth for dry biomass
I_r	[-]	Inhibition percent of *Lemna* growth for fronds' number
K	[mg/l]	Potassium
K.C	[-]	*Lemna* carrying capacity, fronds

K_{ds}	[-]	Ratio of duckweeds' biomass to water salinity in a pond
K_r	[1/d]	First-order salt-removal rate of duckweeds
LOEC	[mg/l]	Lowest observed effect concentration in the *Lemna* test
Mg	[mg/l]	Magnesium
me/l	[-]	Milliequivalent per litre (mg/l ÷ equivalent weight = me/l) in SI units
NaCl	[mg/l]	Sodium chloride
NH_4-N	[mg/l]	Ammonium-nitrogen
Ni	[mg/l]	Nickel
NOEC	[mg/l]	No observed effect concentration in the *Lemna* test
NO_3	[mg/l]	Nitrate
o-PO_4	[mg/l]	Ortho-phosphate
Pb	[mg/l]	Lead
r	[-]	Pearson's correlation coeffient
SO_4	[mg/l]	Sulphate
t_o	[s]	Time at which first water reaches the outlet of a pond
t_m	[s]	Mean residence time of water in a wetland
t_n	[s]	Theoretical residence time of a wetland

TN	[mg/l]	Total nitrogen
TP	[mg/l]	Total phosphorus
TSS	[mg/l]	Total suspended solids
ν	[m²/s]	Turbulent viscosity of water in a pond
VF	[-]	Vertical flow wetlands
ν_T	[m²/s]	Tracer diffusivity in a pond

1 Introduction

Environmental stresses due to lack of water may lead to conflicts and would be greater in poor nations (BAN KI-MOON, 2008). With rapid population growth water withdrawals have tripled over the last 50 years (WORLD BANK, 2007). In 2030, 47 % of world population will be living in areas of high water stress (OECD, 2008). The number of countries without enough water to produce their food is rising as populations increase (UNESCO, 2009). On a global basis, agriculture accounts for 70 % of all water withdrawals, which can rise to 90 % in some developing countries (FAO, 2003). Agriculture needs to expand to produce sufficient food for growing populations with the same amount of water.

Conservation and reuse of agricultural drainage water may be one alternative for freshwater in irrigation. Drainage water is a water supply usable for some purpose within certain quality ranges (KADLEC, WALLACE 2008; FAO, 1999). An estimated 37 % of water withdrawn for agriculture is effectively consumed by plants; a substantial share of the unused water is removed from agricultural lands by flow over or through the soil (UNESCO, 2009). In water - stressed countries, agricultural drainage water is already being reused in irrigation (TALAAT, AHMED 2007; WINTGENS, HOCHSTRAT, 2006). Agricultural drainage water is available in large volumes, and therefore could cover a significant part of total irrigation demand, if adequately managed (WORLD BANK, 2005). Care is taken to minimize the adverse impacts of drainage water reuse on health and

environmental (FAO, 2003). The main components of the agricultural drainage water are nutrients, organic matters, sediments and pesticides (SOROUR et al., 2003; VAN DER VALK, JOLY, 2000).

Wetlands are areas of marsh, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty including areas of marine water (RAMSAR, 1971). Wetlands are widely used as the most cost - effective method for municipal and domestic wastewater treatment with minimal technical and personal efforts (BARJENBRUCH, 2006). In many studies, a number of terms have been introduced for wetlands being natural, restored, created and constructed (HAMMER, 2000; FIELD, 2000; VAN DER VALK, JOLY, 2000). Restored wetlands are areas that previously supported a natural wetland ecosystem but were modified. Created wetlands are wetlands established in areas that historically were not wetlands. Constructed wetlands are created wetlands that were established specifically for wastewater treatment. Wetlands can be also free water surface (FWS) wetlands, horizontal subsurface flow (HSSF) wetlands and vertical flow (VF) wetlands (KADLEC, WALLACE, 2008).

In agricultural landscapes, wetlands are used also for drainage water storage. According to HAMMER, (2000), wetlands in agricultural landscapes may be termed either meadow with 1 - 5 cm water depth, marsh with 10 - 20 cm water depth or ponds with 0.5 - 1 m water depth. Many studies reported that, wetlands or detention ponds in agricultural landscapes are nearly the only effective means for reducing the concentrations of suspended solids, organic matter, nitrogen, phosphorus, and other substances from agricultural drainage water (KADLEC, WALLACE, 2008; STEIDL et al., 2008; ELSAESSER et al., 2007; REINHARDT et al., 2005; JORDAN et al., 2003).

In arid and semi - arid regions, the applicability of detention ponds may be difficult due to high salinity of agricultural drainage water, water scarcity and

evapotranspiration [ET] water loss. The potential salt content of agricultural drainage water in arid and semi - arid regions is on a high level (BAKER, 2000). There are gradual increasing trends in salinity of drainage water over time as a result of repeated reuse (NWRP, 2005). Excessive salinity has the potential of causing serious problems of soil degradation, reduction in crop productivity and degradation of groundwater (FAO, 1999). Salinity affects about 30 million ha of the world's 260 million ha of irrigated land (FAO, 2003). Salinity limits the production of nearly 40 % of agricultural lands all over the world (SERRANO, GAXIOLA, 1994). The salts captured from the agricultural drainage water are the cations Na^{+}, Ca^{+2}, Mg^{+2}, and K^{+}, and the anions Cl^{-}, SO_4^{-2}, and NO_3^{-}, but, the waters are mostly NaCl dominated (NIELSEN, 2000; FAO, 1997). Consideration of these salt loads is important when drainage water is discharged to rivers or lakes or when drainage water is reused for irrigation purposes. Currently many investigations are focused on the use of salt - tolerant plants as crops on saline soils (YASSEEN, AL-THANI, 2007; GLENN, BROWN, 1999). The other strategy which should be taken into account is the application of aquatic salt - tolerant plants to desalinate and purify the water in detention ponds.

Pond design, under all climate conditions, depends on the geomorphological conditions and composition of drainage systems. However, ponds' performance can strongly be influenced by hydraulic design concerning residence time on the one hand and avoiding the hydraulic problems on the other hand. Hydraulic problems such as dead zones, short circuiting and swirling reduce the overall hydraulic and removal efficiency (SHILTON, HARRISON, 2003; OMAR et al., 2010). Dead zones are low - velocity areas where the flow is too slow to mix and interchange fluid with the main flow. However, some water enters and leaves the pond in a very short period of time and this short - circuits the full removal process. The momentum from the inlet causes the swirling.

The problems highlighted above need further investigations to be solved. In order for the detention ponds, generally, to be more effective, sustainable and, particularly, applicable in the arid and semi - arid areas, these questions have to be answered through this dissertation:

- Can detention ponds be managed to remove water salinity?
- Does high salinity influence the nutrient-removal in detention ponds?
- Can evapotranspiration water losses be minimized?
- Can hydraulic problems be minimized?

This work is divided into five chapters.

Chapter 1 presents an introduction to the reuse of agricultural drainage water, detention ponds, and problems that face applicability of such ponds, either generally or, particularly in arid and semi - arid areas.

Chapter 2 shows the latest literatures' review on detention ponds applicability under different conditions; provides information about the suitable plant species for ponds, in particular, under arid and semi - arid conditions, and finally the numerical modelling systems for simulation of such ponds.

In chapter 3, the developed methods are further explained in details including investigations of duckweeds under controlled and natural climate conditions and the numerical simulation of an actual pond.

Chapter 4 shows the results, their analyses, interpretation and the significance of different effects and measures.

Chapter 5 presents the conclusions and the future recommendations.

2 Problem analysis

2.1 Detention ponds

Detention ponds are internationally applicable for agricultural drainage water treatment (SALVATO, BORINA, 2009; STEIDL et al., 2008; ELSAESSER et al., 2007; ANDERSSON et al., 2007). Figure 2.1 shows two different detention ponds in east Brandenburg, Germany. Many studies investigated the removal processes in the detention ponds in agricultural landscapes being sedimentation of nutrients containing particles onto the ponds bottom, filtration of nutrients into the water-permeable soil and vegetation, biological nutrient uptake, mostly by vegetation, adsorption of dissolved phosphorus into the ponds' soil and denitrification of nitrates (KADELAC, WALLACE, 2008; STEIDL et al., 2008; THIERE et al., 2007; EHDE, WEISNER, 2007; WISSING, HOFMANN, 2002; MITSCH 2000; REDDY et al., 1999, HILLBRICHT-ILKOWSKA, 1999; HUNT et al., 1999; KESSLER, JASSON, 1994). The removal efficiency depends on water residence time, hydraulic efficiency, temperature, pollutants' concentrations, vegetation distribution, and light.

Very little consideration was given to the applicability of detention ponds under arid and semi - arid conditions. CASQA, (2003); IQBAL, (1999) reported that detention ponds are less suited in arid and semi - arid regions with scarce water resources. USEPA, (1999) recommended that a larger drainage area may be

required for detention ponds in such areas. Even if large drainage areas are available, evapotranspiration (ET) should be considered. Few data are available about ET loss in detention ponds under all climate conditions. ET can be a very important water loss on a periodic basis (KADLEC, WALLACE, 2008). Experiments in rewetted peatlands under northeast German conditions with negative climate water budget have shown the importance of taking into consideration ET loss (DANNOWSKI, BALLA, 2004). Many aquatic macrophytes such as *Eichhornia crassipes* (water hyacinth), *Typha latifolia* (cattail), *Scirpus validus* (bulrush), *Panicum rigidulum* (panic grass), and *Juncus effusus* (rush) lose big amounts of ET water (RAMEY, SCHARDT, 2004). In arid and semi - arid areas ET water loss can be a big obstacle when such macrophytes are dominant in detention ponds.

Figure 2.1: Two detention ponds in east Brandenburg, Germany

No data is available on the potential of detention ponds to purify and desalinate the agricultural drainage water under high salinity conditions as well as the possibility to reduce ET water loss.

2.2 Vegetation in detention ponds

Aquatic plants in detention ponds have been considered a promising approach to remove different elements from water. Phytoremediation, a plant - based green technology, is a viable alternative for the remediation of contaminated water bodies, not only under experimental conditions but also under natural conditions (MIRETZKY et al., 2004). Besides uptake, KADELAC and WALLACE, (2008) reported that the plants have many other functions in detention ponds. Submerged parts of plants provide support for biofilms facilitating nutrients transformations and organic flocculation. Emergent parts of the plants provide protection from the wind and shading which decreases water temperature and algae growth. Plants provide a range of habitats for macro - and microfauna. Vegetation provides visual contrast through different textures, sizes, shapes and colours. The plants convert atmospheric CO_2 into organic carbon needed by microorganisms which influence many treatment functions regarding water quality (BRIX, HEADLY, 2007).

Selecting the potential plant species to establish in detention ponds is the most significant step. The type of vegetation depends on the goals and objectives for the wetland (SIMERAL, 1998). Improper plant species selection will result in low productivity and a lengthy adaptive period may be necessary until available plant species, either planted or occurring naturally, rearrange themselves (PUIGAGUT et al., 2009; LAING et al., 2007; KNIGHT 2000).

2.3 Duckweeds

2.3.1 The principles

Duckweeds, *Lemnaceae* family, have been selected through this study as the potential plants for the detention ponds generally and in arid and semi - arid areas particularly. Duckweeds are free - floating macrophytes whose structure

possesses only fronds, leaf - like parts, and roots (Figure 2.2). Daughter fronds emerge from the mother frond and later separate to become a new plant. Duckweeds have been selected because of their fast growth, wide distribution, existence in the world from tropic to arctic zone and stability to environmental changes (ISO, 2001). Even in dry conditions, when the aquatic ecosystem dries out, duckweeds have mechanisms to persist until conditions return that can support growth (FAO, 2006).

When conditions are ideal, in terms of water temperature, pH, light and nutrient concentrations duckweed is doubling their biomass in between 16 hours and 2 days (FAO, 2006).

Figure 2.2: Duckweeds (*Lemnaceae* family)

2.3.2 Duckweeds for water treatment

Many studies have proven that duckweeds are highly efficient for wastewater treatment, especially for nutrients' removal (Table 2.1). All abbreviations in this table are explained in the section of acronyms and abbreviations.

Table 2.1: Removal of different parameters by duckweeds from the literatures

Literature	Duckweed species	Parameter	Removal (%)	Method
BAL KRISHNA, CHONGRACK, (2008)	Different	COD	84	Outdoor wastewater treatment system under temperatures from 30 - 36 °C
		BOD_5	88	
		NH_4	68	
		TN	58	
		TSS	87	
EL-KHEIR et al., (2007)	*Lemna gibba*	TSS	96.3	Outdoor natural conditions for eight days at temperature from 20.6 - 29.4 °C
		BOD_5	90.6	
		COD	89	
		NO_3	100	
		NH_4	82	
		PO_4	64.4	
OZENGIN et al., (2007)	*Lemna minor*	COD	73 - 84	Under laboratory conditions
		TN	83 - 87	
		TP	70 - 85	
		PO_4	83 - 95	
EL-SHAFAI et al., (2007) [1]	Different	COD	93	Three ponds under natural conditions during the warm season
		BOD_5	96	
		TSS	91	
		TP	85	
		NH_4	98	
RATTANAPHAN, (2007)	*Lemna perpusilla*	BOD_5	25 - 50	Outdoor pond
		TSS	30 - 50	
		TP	40 - 60	
		COD	30	
SWEIDAN, FAYYAD, (2006) [2]	Different	Phenol	37	Wastewater treatment ponds in Jordan in the spring season
		Detergents	52	
		COD	88.1	

Literature	Species	Parameter	Removal (%)	Method
UYSAL, BZEREN, (2004)	*Lemna minor*	BOD_5	88.8	Under laboratory conditions for three days
		NH_4	85.4	
		PO_4	37.5	
		Cd	75 - 85	
KARA, (2005)	*Lemna trisulca*	COD	92.2	Under laboratory conditions for three days
UYSAL, BZEREN, (2004) [3]	*Lemna minor*	BOD_5	94.7	Under laboratory conditions for six days
		NH_4	75.3	
		PO_4	50	
		Pb	76	
NICHOLAS et al., (2003)	*Lemna minor*	Ni	82	Under laboratory conditions
		BOD_5	90	
IQBAL, (1999)	*Lemna gibba*	Nutrients	74	Sewage lagoon in Bangladesh
		Faecal coliforms	99.8	
		TN	73 - 97	
KÖRNER and VERMAAT, (1998)	Different	TP	63 - 99	Under laboratory conditions for three days

[1] In the cold season, same parameters were also removed parameters except nutrients.

[2] In spring, the percentage removals were (%): COD 22, phenol 24, detergents 29.

[3] For retention time of 3 days, the removal efficiencies for COD, BOD_5, NH_4 and PO_4 were found to be 88.1 %, 88.8 %, 85.4 % and 37.5 %.

In addition, DE CARVALHO et al., (2007) reported that the duckweed (*Lemna minor)* rapidly uptakes pesticides in a 72 h - experiment. Duckweeds can extract excess nitrates and phosphates from the agricultural runoff and degrade many toxic chemicals (JACQUOT, 2008). FAO, (2006) reported that duckweeds have a great potential in decreasing water pollution and increasing the potential for water re-use under arid conditions.

The previous results show that duckweeds are quite successful in purifying the drainage water, but differences in initial concentrations, residence time, light, temperatures, initial biomass of duckweed and experiment settings result in differences in removal efficiencies.

2.3.3 Duckweed and evapotranspiration water loss

The importance of considering evapotranspiration (ET) water loss in the ponds should be considered, since areas of water stress increase worldwide especially in arid and semi - arid areas. One of the benefits of duckweeds is the reduction in water loss in arid and semi - arid regions (ORON et al., 1990). RAMEY and SCHARDT, (2004) reported a comparison between different species of aquatic plants such as *Eichhornia crassipes* (water hyacinth), *Typha latifolia* (cattail), *Scirpus validus* (bulrush), *Panicum rigidulum* (panic grass), *Juncus effusus* (rush), *Alternanthera philoxeroides* (alligatorweed), *Pontederia cordata* (pickerelweed), *Lemna minor* (small duckweed), and *Spirodela polyrhiza* (giant duckweed) with respect to ET water loss. It has been found that all plants will lose water much more quickly than those lakes without plants, since their ET water loss was found to be from 1.2 to 2.7 times greater than evaporation water loss. However, duckweeds were an exception since their ET water loss over evaporation (E) water loss has been found from 0.85 to 0.9 times. ORON and SCHARDT, (1984) reported that a complete cover of duckweed reduces ET by about one - third compared to open water. IQBAL, (1999) mentioned that, among most aquatic plants, duckweed reduced water loss through ET.

2.3.4 Duckweeds and other advantages

Many other benefits of duckweeds have been reported. Reduction in mosquito breeding has been found (IQBAL, 1999; CULLEY et al., 1981). The development of duckweed aquaculture in the wet tropics may have implications for mosquito control in rural areas where malaria is again becoming a serious problem (FAO, 2006). In many ponds, the problem with excessive algal growth that degrades water quality of the effluent was solved by duckweed cover (JACQUOB, 2008; VAN DER STEEN et al., 1998; ALAERTS et al., 1996; HAMMOUDA et al., 1995). DINGES, (1982) compared duckweeds with other aquatic macrophytes being water hyacinth (*Eichhornia crassipes*), pennyworth (*Hydrocotyle umbellata*), water lettuce (*Pistia stratiotes*) and waterfern (*Azolla sp.*). It was found that duckweed is less sensitive to low temperatures, high nutrient levels, pest, pH fluctuations, and diseases.

2.3.5 Potential uses after harvesting

Regular harvesting of duckweeds from the pond to maintain an optimal crop density can play a significant role in controlling duckweed growth and nutrient uptake rates. Some studies have shown that over crowded duckweed could limit growth and can introduce anaerobic degradation within the duckweed mat, and on the other hand, over harvesting that leaves a thin duckweed mat allows light penetration and thus algal growth (REDDY et al., 1985; PORATH et al., 1979). Many studies reported that frequent harvesting improves removal of nitrogen and phosphorus since the duckweed had room to grow (OBEK, HASAR, 2002; IQBAL, 1999). However, the exact value for optimal duckweeds' intensity in such ponds has not been previously provided.

The potential for particular uses after harvesting must be considered. Many researchers suggested suitability of duckweeds for animal feed such as ducks, chickens, prawns, pigs, snails, horses, and ruminants, since duckweeds contain

valuable vitamins, pigments, and minerals and (JACQUOT, 2008; IQBAL, 1999; SKILLICORN et al., 1993; LANDOLT, KANDELER, 1987; HILLMAN, CULLEY, 1978). FAO, (2006) reported that in some regions of the world and particularly during a dry season or in arid areas, where vegetable proteins are scarce, there is considerable scope to improve the nutritional status of the mal - nourished child through the use of duckweed directly or after extraction of a protein from the plant.

Many studies reported that the harvested duckweed from wastewater systems may serve as food for humans and feed for animals (FAO, 2006; IQBAL, 1999; LENG et al., 1995). Nevertheless, it is necessary to be cautious when using the harvested duckweeds from the detention ponds as food for humans and feed for animals because many contaminants can enter the food chain and that needs a strong monitoring before application.

Duckweeds can be used as fertilizer in agriculture with no adverse impacts (FAO, 2006; LENG et al., 1995).

In detention ponds covered with duckweeds, agricultural drainage water might be purified and reused with less evaporation loss on one hand and harvested duckweed might be provided as fertilizer on the other hand. Therefore, such systems may meet the need for sustainable water management.

2.3.6 Duckweeds for saline water treatment

Similar to the effect of duckweeds on nutrient removal, they might attract the concerns regarding the salt removal. Many studies have shown salt - tolerant plants in aquatic systems which sequester the salts in their bodies (KESSELER, JASSON, 2005; FLOWERS et al., 2004; SMITH et al., 2004). Besides technical methods of desalinisation such as multi - stage flash evaporation (MSF) and reversed osmosis (RO), the role of plants in bioremediation increases (PHELPHS, 2007).

Many studies related the ability of salt - tolerance in aquatic plants to regulation of ion concentrations, osmotic adaptation, germination responses and some forms of genetic control (HARE, CRESS, 1998; HOLMBERG, BULOW, 1998; KALAJI, PIETKIEWICZ, 1993; HONG et al., 1992; PITMAN et al., 1983). As an outcome, salt - tolerant plants respond to salt stress at three different levels: cellular, tissue and the whole plant. Other studies reported the involvement of the antioxidative enzymes in salt tolerance in aquatic macrophytes (ROUT, SHAW, 2000; GOSSET et al., 1996; HERNANDEZ et al., 1994).

ELLENBERG et al., (1979) developed indicator values of plants with respect to distinct ecological factors such as temperature, moisture, and salt tolerance. He found that the duckweeds (*Lemna gibba, Lemna trisulca, and Lemna minor*) are floating - submerged and salt - supporting plants. TKALEC et al., (2001) have observed that duckweeds have a long term adaptation during NaCl treatment. JOURNEY et al., (1991) reported that unlike most plants, duckweeds tolerate relatively high concentrations of salts up to about 4,000 mg/l. BUCKLEY et al., (1996) carried out a laboratory experiment on *L. minor* growth under NaCl concentrations: 0, 2.5, 4.3, 7.2 and 12 g/l. It was found that growth decreased when NaCl increased. However, range of salinity concentrations in this study was very high compared to salinity concentrations of agricultural drainage water that range mostly from 0 - 2,000 mg/l in reality and may increase in some stressed areas to 6,000 mg/l (NWRP, 2005; APHA, 1980). FAO, (2006) showed a good ability of duckweeds to tolerate salinity.

Only few data are available on the response of duckweeds to NaCl and no data are available on the salinity uptake of duckweeds or the effect of salt - content on different nutrients - uptakes.

2.3.7 Temperature influence on duckweeds

IQBAL, (1999) reported that minimum water temperature for duckweeds' growth lies at 7 °C, optimum temperatures range between 25 °C and 31 °C, and duckweeds show a severe heat stress at temperatures above 31 °C to 35 °C. ÖBEK and HASAR, (2002) recorded the optimal temperature for duckweed growth is from 20 °C to 30 °C. WATERMANN and BRASSIL, (2009) have tested the growth of duckweeds in two different temperature regimes: 24 °C and 27 °C. Results did not indicate a significant effect of temperature on duckweed growth. LAZFAR et al., (2007) found that duckweeds grow at water temperatures between 5 and 35 °C with optimum growth between 20 and 31 °C. FAO, (2006) reported that duckweeds grow at water temperatures between 6 and 33 °C.

2.4 Assessment of detention ponds' efficiency

2.4.1 Pollutant removal

Once pollutants enter a detention pond, they can exit the pond by volatilization, sedimentation, or by transportation along with water outflow. The pollutants might be transformed inside the pond into other compounds via chemical and biochemical reactions. In addition, the uptake of pollutants by macrophytes happens and is considered the main process that can evaluate the efficiency of a pond. The kinetics or rate of pollutants' uptake by algae can be expressed by the law of mass which was simplified by CHAPRA, (1997) as:

$$\frac{dc}{dt} = -kc^n \qquad \text{[mg/l×d]} \qquad (2.1)$$

Where $\frac{dc}{dt}$ - the change of pollutant concentration in the system over time,

c - the pollutant concentration [mg/l]

k - a temperature - dependent constant [1/d]

n - the reaction order which can be zero -, first -, or second - order

It is very obvious that the reaction rate of pollutants is determined over a time period. The time that a pollutant stays in a detention pond is defined as the hydraulic residence time. Sufficient time allows sufficient pollutants' removal by macrophytes. The effect of hydraulic residence time was identified in many studies as the main factor controlling removal of nutrients and other elements in the depression forms used for agricultural drainage water (FAO, 2006; REINHARDT et al., 2005; MITSCH, 1992).

2.4.2 Growth of macrophytes

Many macrophytes such as duckweeds require also sufficient time to grow and multiply. CHAPRA, (1997) used first - order reactions to model the growth of free floating algae as following:

$$\frac{da}{dt} = k_g a \quad \text{[mg/d]} \qquad (2.2)$$

Where a - algae mass [mg]

k_g - a first - order growth rate [1/d]

JEFFERIES, (1991) also described the exponential growth of duckweeds as:

$$\frac{dN}{dt} = rN \qquad (2.3)$$

Where N - the number of fronds, leaf - like parts, in the population [frond], and

r - the intrinsic rate of increase [1/d]

2.4.3 Residence times

The hydraulic residence time is an important hydraulic factor influencing the both, hydraulic and treatment efficiency of detention ponds. It is the average time a substance spends within a pond. It also expresses the time that the water volume takes to leave the pond.

According to SHILTON and HARRISON, (2003); WERNER and KADLEC, (1996) the theoretical residence time, t_n, is simply calculated by:

$$t_n = \frac{V}{Q} \quad [d] \qquad (2.4)$$

Where V - pond volume [m^3]

Q - average flowrate [m^3/d]

In reality ponds do not operate at their theoretical hydraulic residence time and this is because dead zones, short - circuitings and swirlings are found. The mean residence time, t_m, and theoretical residence time, t_n, are equal only for constant flow systems (steady - flow systems) (WERNER, KADLEC, 1996; FOLGER, 1992).

To determine t_m and the residence times distributions (RTDs) of a pond, a tracer test should be undertaken. There are many tracer studies of treatment wetlands (WERNER, KADLEC, 1996). The RTDs quantifies the distribution of detention times for a given wetland (KADLEC, 1994). The purpose of generating the RTDs from tracer studies is to better understand the hydrodynamics of the pond. RTD theory is widely used in the study of flow and mixing in constructed wetlands (KADLEC, 1994; KNIGHT, 1994; EGER, 1992; PAULY, ODENTHAL, 1990).

Mean residence time alone is not enough to evaluate the pond hydraulic and treatment efficiency. It is possible to have two ponds with the same t_m but with

different hydraulic and treatment efficiencies (SHILTON, HARRISON, 2003). According to THACKSTON, (1987) the ratio between t_m and t_n can be illustrated with the effective volume ratio, e, or the hydraulic efficiency:

$$e = \frac{t_m}{t_n} \quad [-] \quad (2.5)$$

2.5 Numerical flow and transport simulations of detention ponds

A sustainable management and protection of water in the environment is one of the key problems of the 21st century, and numerical simulation models will contribute considerably to its solution.

An improved understanding of flow and transport processes of ponds is needed in order to find the best design concerning hydraulic and removal efficiency. HINKELMANN, (2005) explained the use of numerical simulation models in environment water as describing the flow with transport processes and predicting the consequences of changing conditions. Models are the most efficient and inexpensive way to describe and optimize such ponds. Therefore, in addition to experiments, much research has been done using computer modelling in recent years.

Both physical and numerical model investigations of water disinfection tanks, similar to detention ponds, have been undertaken by RAUEN et al., (2008). A 3D computational fluid dynamics (CFD) software was developed to simulate the flow processes of such tanks. The validation analyses confirmed the appropriateness of the numerical modelling approach for simulating and optimising the design of tanks. However, the CFD software is less suitable for the surface water systems.

KOSHIAHO, (2002) examined hydraulic properties of two constructed wetland - ponds in agricultural watersheds in southern Finland by simulations with two dimensional hydrodynamic and transport modelling. Hydraulic efficiency was obtained for the existing and hypothetical layouts of both wetlands to determine the effect of different design options.

MOUSTAFA and HAMRICK, (2000) have developed the Everglades Wetland Hydrodynamic Model (EWHM) which was used to provide an accurate description of the hydrodynamic processes in a wetland. This model presented a notable advancement in describing 2D flow across vegetated areas and used to simulate tracer releases and estimate the hydraulic residence time in wetlands.

Other 2D models have been presented for simulation of wetlands including vegetation resistance (ZHAO et al., 1992). SHILTON and HARRISON, (2003) used computer simulation using PHOENICS Computational Fluid Dynamics (CFD) software for the potential hydraulic improvements of ponds due to different inlet, outlet and shape configurations.

It is obvious that numerical simulations have been internationally used in many studies. However, each pond has its own individual characteristics with regard to influent flows and loads; shape; and environmental conditions (SHILTON, HARRISON, 2003). Therefore, many sensitivity studies concerning dominant parameters such as discharge, bottom friction, turbulent viscosity and diffusivity, and inlet design as well as addition of design features such as baffles should steadily be investigated to improve performance of each pond individually. That requires more attention on applying the numerical modelling systems to simulate and optimize the ponds with respect to it hydraulics and uptake rate of its macrophytes. Modelling such ponds should consider many special difficulties such as low flow velocities, plants' resistance along the water column. Moreover, the uptake reaction transport is also required.

2.6 Baffles for optimization of ponds

Baffles are walls or plates used widely to control and direct the flow in ponds or wetlands. The use of baffles can lengthen the flow path and hence increase the residence time. In addition, baffles can minimize the hydraulic problems in ponds such as dead zones, short - circuitings and swirlings and, subsequently, improve the hydraulic and treatment efficiency of ponds. Baffles as part of the original shape of detention ponds have differing effects on different ponds. The length, number and positioning of baffles has been extensively investigated using computer modelling, and both laboratory and field testing. WATTERS, (1973) undertook an in - depth study on different lengths of baffles: 50 %, 70 % and 90 % of the width of pond. It was found that baffles of 70 % width gave superior performance compared to 50 % and 90 % width. SHILTON and HARRSIN, (2003) undertook a series of models to investigate the influence of baffles' number on removal efficiency. Based on the results of this study, a minimum of two baffles was recommended and more than four baffles were not recommended. KOSHIAHO, (2002) used the numerical simulations to test the effect of baffles on performance of two actual constructed wetland - ponds. Hydraulic efficiency was found to be highly improved in both ponds by baffles that directed the main flow to optimally exploit the wetland acreage. For every specific pond, investigations on number and length of baffles to be installed should be undertaken. Baffles have differing effects on different ponds. For every specific pond, investigations on the number and length of baffles to be installed are still required.

2.7 Literatures conclusions

Many studies have investigated the potential of detention ponds for storage and treatment of agricultural drainage water. Much research has been done using the numerical modelling to simulate the hydrodynamic and transport processes

of detention ponds and predict the consequences of design modifications by baffles. Many research studies have investigated the potential of duckweeds' species for uptake of different pollutants from water under both laboratory and natural conditions.

The main conclusions of those studies are:

1. Detention ponds are of high efficiency for removal of different parameters from the water, mostly by vegetation uptake.
2. Duckweeds have proven the efficiency to remove many elements.
3. Design modification by baffles increased both the hydraulic and efficiency of the detention ponds.

However, the applicability of detention ponds must consider, generally, the hydraulic problems, and particularly, the high salinity of drainage water as well as evapotranspiration water loss. Very little consideration has been given to the applicability of detention ponds under arid and semi - arid conditions. No data is available on the potential of detention ponds if the drainage water is of high salinity and is exposed to high evapotranspiration water loss. Duckweeds in detention ponds under high salinity conditions have not been yet investigated. Only few data are available on the response of duckweeds to different water salinities and no data are available on the salinity uptake of duckweeds or the effect of salinity on different nutrients - uptakes. The value of initial duckweeds' intensity in such ponds that can achieve the highest removal efficiency and least evaporation water loss has not been previously provided.

From the literatures' conclusions mentioned above there are some aspects need further investigations. Therefore, the main purposes of the present study are:

1. Proof of the salt - tolerance and salt - uptake function of duckweeds.

2. Investigation of baffles' influence on residence time, hydraulic efficiency and salt - uptake efficiency in detention ponds.

3 Experimental, numerical and statistical methods

The main questions needed to be answered were:

- Can duckweeds survive under saline conditions?
- What is the salt - concentration threshold for duckweed growth inhibition?
- Does salinity influence the nutrient - removal of duckweeds?
- What is the salt - uptake kinetics' rate of duckweeds?
- Does the duckweeds biomass intensity affect both, the salt - removal and evaporation water loss?
- Do the dominant parameters such as bottom friction, turbulent viscosity, inlet design, and flood conditions influence both, the flow and transport processes of detention ponds?
- Can design modifications by baffles improve the hydraulic and treatment efficiency of detention ponds?

To answer these questions, laboratory investigations have been undertaken under both, controlled and natural climate conditions. In addition, numerical simulations of detention ponds have been carried out.

3.1 Investigations under controlled climate conditions

3.1.1 *Lemna* growth inhibition test

This test is generally designed to assess the toxicity of substances dissolved in water to fresh duckweed *Lemna* species. The *Lemna* species is used as model organism for higher aquatic plants. *Lemna* are allowed to grow as monoculture in different concentrations of the test substance over a period of seven days. The general objective of this test is to quantify the growth inhibiting response of substances contained in water, as well as in treated municipal and industrial effluents.

3.1.2 *Lemna* test with respect to salinity

3.1.2.1 Purpose

Lemna test was used in this work based on the existing guidelines provided by (ISO, 2001; OECD, 2002) but many modifications were included to match the objectives of the work. *Lemna* test has been undertaken to:

1. Assess the effect of salinity, in particular, NaCl and temperature on the growth rate of *Lemna minor*, one species of the *Lemnaceae* family.
2. Investigate the desalination and salinity effect on nutrient removal over seven days.

3.1.2.2 Test procedures

Lemna minor was collected from a pond in the surrounding. Green fronds without visible lesions were washed by deionised water and cultured in a 900 - ml Swedish Standard (SIS) medium (Table 3.1). The culture was incubated in a climate chamber at the Institute of Landscape Matter Dynamics, Leibniz Centre

for Agricultural Landscape Research (ZALF) under temperature at 25 °C, light intensity 8000 lux and photosynthetically - radiation 100 μ E m^2/s for one week to adapt to the test conditions. Eleven fronds from culture were transferred systematically into test vessels with different NaCl concentrations with three replicates each.

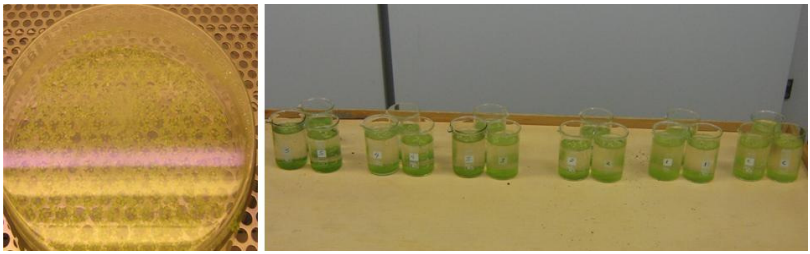

Figure 3.1: Test medium (left) and groups of NaCl concentrations (right)

At temperature 25 ºC, tests 1 and 2 were carried out under large range of NaCl concentrations (0 - 10000 mg/l), and tests 3 and 4 under low range of NaCl concentrations (0 - 500 mg/l). At temperature 35 ºC, test 5 was under concentrations of 0 - 10000 mg/l, and test 6 under concentrations of 0 - 500 mg/l. At temperature 5 ºC, test 7 was done under concentrations of 0 - 10000 mg/l, and test 8 under concentrations of 0 - 500 mg/l. Test 1 and 3 were undertaken in the year 2008 and the others in 2009. *Lemna minor* in test 1 and 3 that were undertaken in 2008 differed from those used in the other tests undertaken in 2009. The reproducibility has been considered in this test, where:

1. Many tests have been done under the same conditions.

2. For every NaCl concentration, three replicates have been provided.

The culture solution was used as control and dilution for solutions. The initial total salinity of solutions exceeded their nominal NaCl concentration due to the salinity of culture solution (Table 3.2).

Table 3.1: Test medium for *L.minor* growth (Swedish Standard (SIS))

Substance	Abbreviation	Concentration (mg/l)
Magnesiumsulfatheptahydrat	$MgSO_4*7\ H_2O$	75
Sodium nitrate	$NaNO_3$	85
Calcium chloride dihydrate	$CaCl_2*2\ H_2O$	36
Sodium carbonate	Na_2CO_3	20
Potassium dihydrogen phosphate	KH_2PO_4	13.4
Boric acid	H_3BO_3	1
Manganese chloride tetrahydrate	$MnCl_2*4\ H_2O$	0.2
Sodium Molybdate Dihydrate	$Na_2MoO_4*2\ H_2O$	0.01
Zinc Sulfate Heptahydrate	$ZnSO_4*7\ H_2O$	0.05
COPPER SULFATE PENTAHYDRATE	$CuSO_4*5H_2O$	0.005
Cobalt nitrate	$Co(NO_3)_2*6\ H_2O$	0.01
Disodium Ethylene Diamine Tetraacetate Dihydrate	Na2EDTA Disodiumdihydrate	1.4
Ferric chlorid hexahydrate	$FeCl_3*6\ H_2O$	0.84

Table 3.2: Nominal and total salinity concentrations

Large range		Low range	
NaCl (mg/l)	Salinity (mg/l)	NaCl (mg/l)	Salinity (mg/l)
0 (Control)	380	0 (Control)	205
500	1297	20	238
1000	1862	80	315
2500	3612	150	410
5000	6447	250	519
10000	11571	500	844

The initial dry weight was measured after sub - samples of the fronds were rinsed with deionised water, kept on absorbent paper for 15 minutes to remove water, taken into a ceramic dish and dried for 24 h at 60 °C. Initial salt, anions and cations concentrations were measured. After the test was finished, the final fronds were counted and final dry weight and final concentrations of salts, anions and cations in each solution were measured.

3.1.2.3 Data analysis

The response of *Lemna minor* to different NaCl concentrations was assessed by the following parameters obtained according to OECD, (2002):

1. Specific growth rate (μ) for each test concentration or control group:

$$\mu = \frac{\ln(N_7) - \ln(N_0)}{T_7 - T_0} \quad [-] \quad (3.1)$$

Where $\ln(N_0)$ - the natural logarithm of fronds' number in the test or control vessels at the beginning of the test

$\ln(N_7)$ - the natural logarithm of fronds' number in the test or control vessels at the end of the test

T_0 - time for the start of the test [d]

T_7 - time for the end of the test [d]

2. Inhibition of growth rate of frond number (I_r) for each test concentration:

$$I_r = \frac{(\mu_C - \mu_T)}{\mu_C} \times 100 \quad [\%] \quad (3.2)$$

Where μ_C - value for μ in the control group [%]

μ_T - value for μ in the treatment group [%]

3. Inhibition of growth rate of dry biomass (I_b) for each test concentration:

$$I_b = \frac{(b_C - b_T)}{b_C} \times 100 \quad [\%] \quad (3.3)$$

Where b_C = ln(final biomass) - ln(starting biomass) for the control group

b_T = ln(final biomass) - ln(starting biomass) for the treatment group

4. The NaCl concentration causing 50 % of growth inhibition (EC_{50}).

5. The lowest observed effect concentration (LOEC). LOEC was the lowest concentration at which the substance had a statistically significant reducing effect on growth.

6. No observed effect concentration (NOEC). NOEC was the test concentration immediately below the LOEC which, when compared with the control, had no statistically significant effect.

In addition, two parameters have been determined concerning the uptake of duckweeds being the salinity - removal rate and nutrient - removal rate.

3.1.3 Logistic growth of *Lemna minor*

3.1.3.1 Purpose

The logistic population growth model of *Lemna minor* generally shows how the growth changes over time. The growth is observed by counting the fronds' number always after a constant time period (here every 2 days). The logistic growth model is used to:

1. Determine the *Lemna minor* carrying capacity (KC) at which the frond number becomes constant after a period of time because the growth slowed to almost zero.

2. Estimate the intrinsic rate of increase (r_g).

With respect to salinity, logistic growth models of *Lemna minor* under different NaCl salinities have been obtained in order to describe how different water salinities affected the growth of *Lemna minor* over time.

3.1.3.2 Test procedures

Procedures of collection and culture of *Lemna minor* followed the *Lemna* - test guidelines as explained previously. NaCl concentrations of control, 20, 80, 150, 250, 500, 1000, 2500, 5000, and 10000 mg/l were tested. Six fronds from the culture were transferred systematically into test vessels with 100 ml of different NaCl concentrations with three replicates each. The test continued until *Lemna minor* approached its carrying capacity (KC).

3.1.3.3 Data analysis

The fronds' number was counted every two days and the change in fronds' number per day per frond was obtained. When the maximum change occurred, the intrinsic rate of increase (r_g) was determined according to JEFFERIES, (1991) as follows:

$$N_t = N_o e^{r_g \times t} \quad [-] \quad (3.4)$$

Where N_t - the final number of fronds

N_o - the initial number of fronds

e - Euler's number

r_g - the intrinsic rate of increase

t - the length of the time period being two days

3.2 Investigations under natural climate conditions

3.2.1 Phase (1)

3.2.1.1 Purpose

It was important to carry out investigations on duckweeds under natural climate conditions to proof the results of the tests under controlled climate conditions. The experiment in its first phase was undertaken in order to:

1. Assess the effect of salinity on the growth rate of duckweeds *Lemna minor* and *Spirodela polyrhiza,* two species of the *Lemnaceae* family, under natural climate conditions.

2. Investigate the desalination function of duckweeds.

3. Investigate the salinity effect on nutrient removal.

3.2.1.2 Experimental basis

Duckweeds were investigated in two outdoor containers under natural climate conditions with actual drainage water of different salinities in the period from June to August, 2008. The investigations have not been undertaken in an actual detention pond for two reasons being:

1. Protection of the ground water and outflow receiving waterways from the extra salts added to the water during the investigations.

2. Adaptation of duckweeds to salinity and salt - uptake rate over time required a long residence time and no inflow and outflow. Such conditions were too difficult to achieve in a real pond.

The main processes affecting the salt - mass changes in both containers are presented in (Figure 3.2) as follows:

1. Changes due to precipitation (P) and evaporation (E), where:

   C_p - salt concentration in precipitation [g/m^3]

   V_P - water volume of precipitation [m^3]

   C_E - salt concentration in evaporation [g/m^3]

   V_E - water volume of evaporation [m^3]

2. Sedimentation of dead biomass or particles.

3. Transformation processes.

4. Accumulation in duckweeds' biomass.

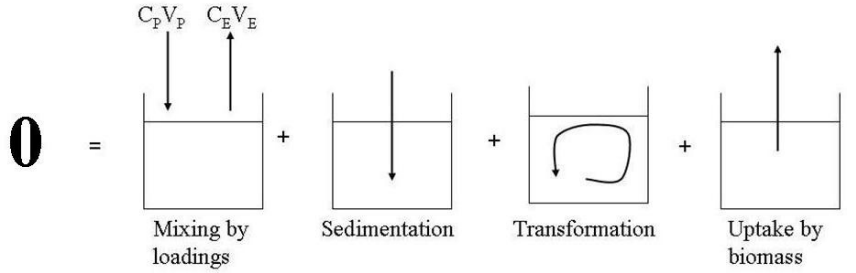

Figure 3.2: Main processes of salt - mass changes

3.2.1.3 Experimental procedures

In phase (1), two containers were used with dimensions shown in (Figure 3.3). The containers were filled with drainage water transported from a detention pond nearby Müncheberg (State of Brandenburg, Germany). The chemical characteristics of drainage water are shown in (Table 3.3), where all abbreviations are explained in the section of abbreviations and acronyms. The first container, as control, was not charged by extra salt. The electrical conductivity (EC) as a measure of salinity in the first container was 800 µS/cm (0.56 g/l). The second container was loaded by extra NaCl up to 1800 µS/cm (1.26 g/l). Initial water depth of 60 cm resulted in volume of approx. 1750 l. The water volume was estimated to achieve a sufficient nutrient - supply for duckweeds' growth over a period of time in which duckweeds covered the full surface area of containers.

Duckweeds were collected from the pond in the surrounding and washed with deionised water. 400 g of green duckweeds was transferred into each container as initial biomass after attached algae were removed. Final duckweeds were removed from the containers for analysis, and then 400 g was transferred again from the final duckweeds into the containers for further investigations. The

removal of final duckweeds from the containers occurred by the end of week 2, 5, 7 and 10. After the experiment was repeated, the final duckweeds were removed by the end of week 2, 5 and 7.

Final duckweeds biomass was weighted. Samples of initial and final duckweeds were centrifuged and EC of the resultant solutions were measured. The dry biomass analysis of initial and final duckweeds' samples was also carried out at the Central lab of ZALF.

The water depth in containers was measured daily by a ruler with an accuracy of 1 mm. The precipitation was measured daily by a simple rainfall gauge. EC in the water of containers and precipitation were measured daily. Changes in nutrient loads were determined by water quality analyses before and after the experiment.

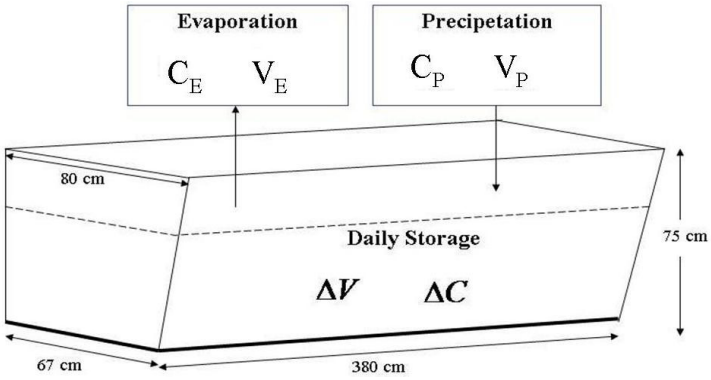

Figure 3.3: Mass balance in the container

Figure 3.4: Container with drainage water, initial addition of duckweeds and final duckweeds cover

Table 3.3: Chemical characteristics of drainage water in the containers

Parameter	Unit	Concentration
1. Salinity		
EC	µS/cm	800
TDS	mg/l	560
2. Cations and anions		
Ca^{+2}	mg/l	210
K^{+}	mg/l	13.5
Mg^{+2}	mg/l	19.5
Na^{+2}	mg/l	27
NO_3^{-}	mg/l	158
Cl^{+2}	mg/l	49.7
SO_4^{-2}	mg/l	127
PO_4^{-}	mg/l	0.188

3.2.1.4 Data analysis

The general mass balance according to KADLEC and WALLACE, (2008) was:

$$\frac{d(V \times C)}{dt} = A \times P \times C_P - \Delta V_S C_S - \Delta V_T C_T - A \times J \qquad [g/d] \qquad (3.5)$$

Where V - water volume in the container [m^3]

C - salt concentration of water [g/m^3]

A - surface area [m^2]

P - precipitation rate [m/d]

C_p - salt concentration in precipitation [g/m^3]

$\Delta V_S C_S$ - salt mass in sedimentation [g/d]

$\Delta V_T C_T$ - salt mass transformed by biological and chemical reactions [g/d]

J - the salt removal rate by duckweeds [$g/m^2 \times d$]

It was assumed that there were no salt losses by sedimentation, transformation or evapotranspiration in the containers. The changes in salinity were caused only by both, changes in water volume and accumulation in duckweed tissue. Therefore, the mass balance in the containers can be simplified to:

$$\frac{d(V \times C)}{dt} = A \times P \times C_P - A \times J \qquad [g/d] \qquad (3.6)$$

The salt removal rate of duckweeds $(A \times J)_D$ was the difference between salt load input by precipitation and changes in mass storage as follows:

$$(A \times J)_D = A \times P \times C_P - \frac{d(V \times C)}{dt} \qquad \text{[g/d]} \qquad (3.7)$$

Salt accumulation in duckweeds' tissues was also estimated by observing the difference between the EC values of duckweeds' solutions before and after exposure to the drainage water.

Accumulation of N^{-3}, P^{-4}, and NO_3^- in duckweeds' tissues was determined by the dry biomass analysis for samples before and after exposure to drainage water. Removal of Ca^{+2}, Mg^+, P^{-4}, K^+ and NO_3^- was obtained as the difference between initial and final mass in water.

3.2.2 Phase (2)

3.2.2.1 Purpose

Based on the results of phase (1) in 2008, more experience has been gained with respect to growth cycle, nutrient - demand, water depth and volume. Phase (2) has been undertaken in 2009 with further new modifications. Duckweeds were investigated under three different salinities during the spring - summer period. For each salinity, one duckweeds - covered (with duckweeds) tank and one open - water (without duckweeds) tank were prepared.

In addition to the purposes of phase (1), this phase considered further purposes including:

1. Estimation of the salt - removal kinetics reactions of duckweeds.
2. Proof of the duckweeds' potential for evaporation water loss reduction.
3. Investigation of the duckweeds' biomass influence on salt and nutrient removal as well as evaporation water loss.

3.2.2.2 Experimental procedures

Six small tanks in series were filled with water of depth 10.6 cm resulting in approx. 20.5 litres. Two tanks, as control with electrical conductivity EC = 930 µS/cm (0.6 g/l), were not charged by extra salt. The sequent two tanks were loaded by extra NaCl up to EC = 2280 µS/cm (1.6 g/l) and the last two tanks up to EC = 3040 µS/cm (2.1 g/l). One duckweeds - covered tank and one open - water tank were prepared for each certain salinity. EC of water in tanks and precipitation, water level, precipitation was measured daily. Two subsequent experiments were carried out with initial duckweeds' biomass of 50 and 30 g resulting in duckweed intensity of 260 and 160 g/m^2, respectively.

3.2.2.3 Data analysis

The principle of mass balance was used also in this experiment for obtaining the salt removal efficiency of duckweeds. The salt - removal has been obtained for the duckweeds - covered tanks as following:

$$(A\times J)_D = A\times P\times C_P - \frac{d(V\times C)}{dt} \qquad \text{[g/d]} \qquad (3.8)$$

The salt - removal of open - water tanks without duckweeds was not available in the previous experiment and was obtained as following:

$$(A\times J) = A\times P\times C_P - \frac{d(V\times C)}{dt} \qquad \text{[g/d]} \qquad (3.9)$$

The salt - removal of open - water tanks represented any other components of salt - removal that had not been considered in the previous experiment as well as those assumed zero such as sedimentation or transformation.

The actual salt removal of duckweeds ($\Delta A \times J$) was determined as the difference between the salt removal in the duckweeds - covered tank in Eq. (3.8) and open - water tank in Eq. (3.9) as followings:

$$\Delta A \times J = (A \times J)_D - (A \times J) \qquad \text{[g/d]} \qquad (3.10)$$

As in the previous experiment, accumulation of N^{-3}, P^{-4}, NO_3^-, Na^+, Cl^-, NH_4^- and salts in duckweeds' tissue was obtained.

The water balance has been applied for obtaining both, the evaporation water loss over the open - water tanks and evapotranspiration water loss over the duckweeds - covered tanks. The general water balance according to CHAPRA, (1997) was:

$$S = \frac{dV}{dt} = Q_{in} - Q_{Out} + G + P \times A \; - ET \times A \qquad [m^3/d] \qquad (3.11)$$

Where S - water storage [m^3/d]

V - volume [m^3]

t - time [d]

Q_{in} and Q_{out} - inflow and outflow [m^3/d]

G - groundwater flow [m^3/d]

P - precipitation rate [m/d]

A - surface area [m^2]

The (ET) in the equation represented the evapotranspiration water loss over the duckweeds - covered tanks or the evaporation water loss over the open - water tanks. Since there was no inflow, outflow and infiltration to ground water in the

tanks, the estimated daily evapotranspiration or evaporation volume (ET×A) was as following:

$$ET \times A = P \times A - S \qquad [m^3/d] \qquad (3.12)$$

(ET×A) for each tank was determined as the difference between precipitation and measured changes in storage.

3.3 Numerical simulation of a pond

3.3.1 Purpose

An actual detention pond in East Brandenburg, Germany has been investigated using numerical flow and transport simulations. 2D simulations have been chosen for the simplification which was based on many reasons being:

1. The water depth in the pond was small (maximum = 0.65 m).
2. The hydrostatic pressure was low.
3. Only the horizontal flow velocity has been considered but the vertical one has been ignored as a result of the small water depth.

The simulations have been carried out for considering the following aspects:

1. Description and understanding of the hydrodynamic and transport processes of the pond as well as estimation of the hydraulic residence time.
2. Prediction of consequences of a number of sensitivity studies concerning many dominant parameters such as flood conditions, inlet design, bottom friction, and turbulent viscosity and diffusivity.

3. Assessment of the influence of length, number and position of baffles on the hydraulic properties and efficiency as well as the salt - removal efficiency.

3.3.2 Study area

The study pond is one of three detention ponds established by the Institute of Landscape Hydrology, Leibniz Centre for Agricultural Landscape Research (ZALF) as a research project. The project is focused on proofing its functioning as well as formulating of design criteria and principles for detention ponds to reduce nutrients' loads from drainage systems. The pond is located nearby Müncheberg, Brandenburg State, Germany. The pond of 0.05 ha drains a 5.1-ha agricultural area and the downstream receiving water is Stöbber River (Figure 3.5). The pond is located in a natural depression and the bottom soil is loam.

The discharge to the pond flows via a subsurface collector pipe is controlled by a V - notch weir. Both, the subsurface pipe and the weir, are installed inside a bricks - box and the inflow enters the pond through another pipe installed at lower level near to the bottom to prevent inflow disturbance and soil erosion (Figure 3.6). The height of the inlet weir is 10 cm resulting in discharges from 1 - 3 l/s. A similar V - notch weir is installed at the outlet. A data - logger collects the discharges at both, the inlet and outlet to collect discharge data. Survey works have been done previously and the resulting bathymetry was used in the modelling.

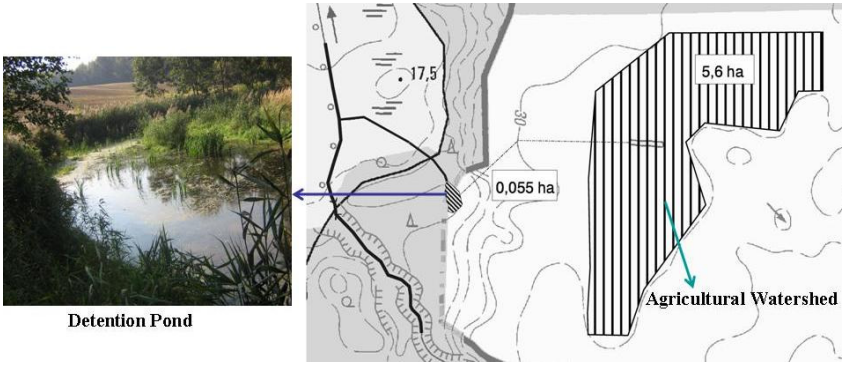

Figure 3.5: The detention pond and its drained agricultural watershed

Figure 3.6: The inlet with an automatic water sampler (left) and V - notch weir (right)

3.3.3 Modelling system

The modelling system TELEMAC - 2D has been used for the simulation and optimization of the pond. This program solves the depth - averaged free surface flow and transport equations using the Finite Element Method (FEM) (HERVOUET, 2007; HINKELMANN, 2005). The computational domain in the FEM is subdivided in many small finite elements with nodes. The main results

at each node of the computational mesh are depth of water and depth - averaged velocity components as well as the tracer concentrations.

The equations for the flow and transport processes in surface - water systems are as followings:

flow equations (2D):

$$\frac{\partial h}{\partial t} + \underline{v}\ grad\ \ h + h\ div\ \underline{v} = q_w \tag{3.13}$$

$$\frac{\partial \underline{v}}{\partial t} + \underline{v}\ grad\ \underline{v} - div(\underline{\underline{\upsilon}}_{th}\ grad\ \underline{v}) = \frac{1}{\rho}\underline{f} - g\ grad\ (h + z_b) \tag{3.14}$$

Where grad - a vector field having coordinate components that are the partial derivatives of a function with respect to its variables

div - an operator that measures the magnitude of a vector field's source or sink at a given point in terms of a signed scalar

h - the water depth [m]

z_b - the bottom elevation [m]

$\underline{v}$ - the velocity vector of the free - surface flow

q_w - a sink or source term of water

$\underline{\underline{\upsilon}}_{th}$ - the horizontal viscosity tensor (physical, turbulent)

ρ_w - the density of water [kg/m^3]

p - the pressure [N/m^2]

f - a momentum source term

Manning friction law can be written as follows:

$$v = \frac{1}{n}(R)^{2/3}\ S_L^{\ 1/2} \tag{3.15}$$

Where, n - Manning roughness coefficient [s/m$^{1/3}$]

R - the hydraulic radius [m]

S_L - the bottom slope [-]

transport equation (2D) for a tracer S:

$$\frac{\partial S}{\partial t} + \underline{v}\ grad\ S - div(\underline{\underline{\upsilon}}_{t,th}\ grad\ S) = q_S \tag{3.16}$$

Where $\underline{\underline{\upsilon}}_{t}$ - the diffusivity tensor (physical, turbulent)

q_S - a tracer sink or source term of water

For the advection, upwind schemes have been applied applied. BiCGSTAB was chosen as the solver (method for the iterative solution of large and typically sparse systems of linear equations with a non - symmetric matrix) (HINKELMANN, 2005).

The modelling system TELEMAC - 2D has been also applied by Jourieh et al., (2006) for numerical simulation of flow and transport processes of combined sewer overflows spreading into the city's main river, the Spree which is a very slowly flowing urban river. However, the flow velocity in the detention pond is very small compared to those velocities in the river Spree.

3.3.4 Modelling procedure

The work has been done in three steps (pre - processing, processing, and post - processing). The module MATISSE was used for the pre - processing, the module TELEMAC - 2D for the processing, and the module RUBENS for the post - processing.

In the pre - processing stage, the module MATISSE has been applied here to introduce the boundaries and bathymetry of the model. The computational mesh consisted of triangular elements (Δx = 1 m) and was refined around the pond inlet and outlet (Δx = 0.1 m) (Figure 3.8). The geometry and boundary condition files have been generated for the simulation modules. On the open upstream boundary, constant discharge was prescribed and on the downstream boundary, water level was imposed. The tracer source was chosen as a point near to the inflow. The deepest bottom elevation was found in the middle (0 m) and the highest bottom elevation was found around the inlet (0.65 m) (Figure 3.7).

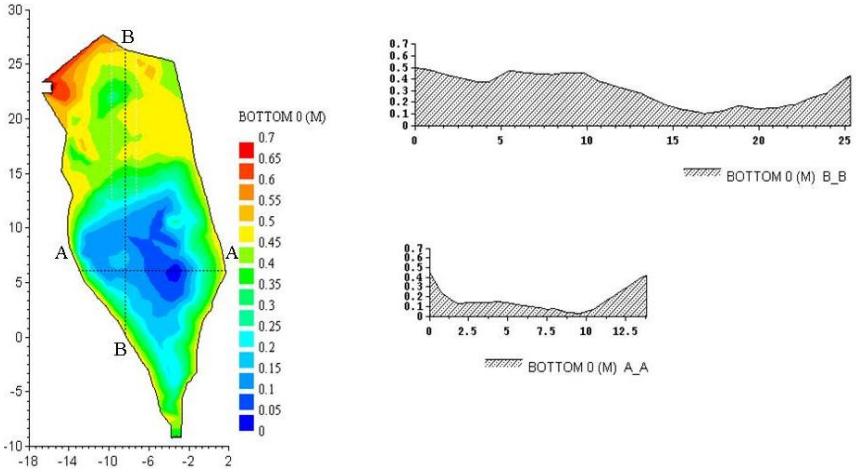

Figure 3.7: The topography of the pond

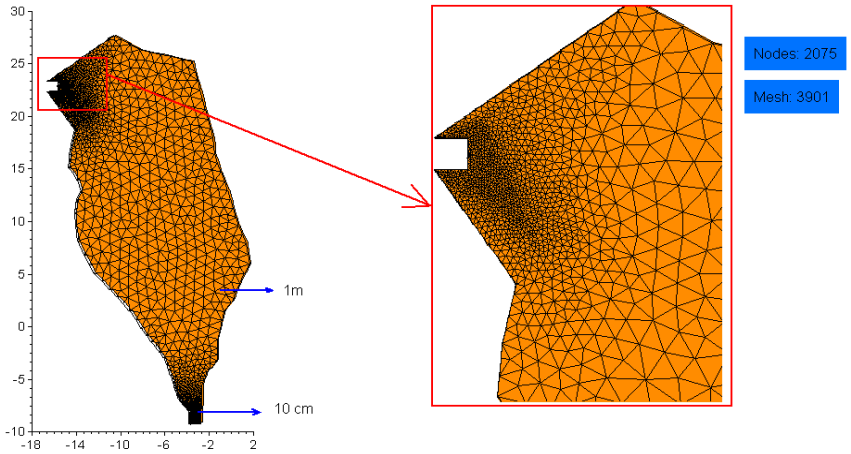

Figure 3.8: The computational mesh of the pond

The processing in TELEMAC - 2D was controlled by a steering file which contained data such as file names for input and output, initial and boundary

conditions as well as physical and numerical parameters. The time step was 0.3 seconds which corresponds to courant number of C_r = 1. As initial condition, the flow velocities were zero, and the initial water level was set to 0.9 m.

Reynolds number was used to determine whether the flow in the pond was laminar or turbulent. Reynolds number (R_e) is calculated as follows:

$$R_e = \frac{vL}{\upsilon} \qquad [-] \qquad (3.17)$$

Where v - the mean flow velocity [m/s]

L - the characteristic length or hydraulic radius = water depth of the pond [m]

υ - the kinematic viscosity [m²/s]

If $R_e \leq 2300$, the flow is laminar, and

$R_e \geq 2300$, the flow is turbulent.

It was expected that the flow was laminar, because the flow velocities were small. Nevertheless, R_e has been calculated for all scenarios at different locations of the pond. High viscosity was assumed to consider the existence of plants via the pond.

The general case represented the original conditions of the pond before changing its dominant parameters or setting baffles' configurations. For the general case, the inflow discharge was imposed with a constant value of Q = 0.003 m^3/s. The friction coefficient of Manning was n = 0.05 $s/m^{1/3}$ according to MARTIN-VIDE et al., (2008) who obtained the n values in a flume with different discharges and plastic strips simulating vegetation. A constant turbulent viscosity was chosen with a value of υ = 0.01 m²/s.

Tracer transport simulations were done to investigate the spreading of a conservative tracer. Tracer simulations were used in this study to elucidate the actual water volume of the pond, as well as the degree of apparent mixing. Residence time distributions, RTDs, were generated from tracer simulations to better understand the mixing and the hydrodynamics. The tracer flow duration was 10 minutes. The viscosity and the diffusivity were set equal ($\upsilon = \upsilon_t$ = 0.01 m²/s).

According to SHILTON and HARRISON, (2003), the mean residence time (t_m) was defined as:

$$t_m = \frac{\sum_{i=1}^{i=n} t_i \times C_i \times \Delta t}{\sum_{i=1}^{i=n} C_i \times \Delta t} \quad [d] \qquad (3.18)$$

Where t_i - the time at i_{th} time increment [d]

C_i - the tracer concentration at i_{th} time increment [-]

n - number of time steps

Δt - the time increment (here 2000 s)

The theoretical residence time (t_n) has been obtained from Eq. (2.4) and the hydraulic efficiency (e) of the pond from Eq. (2.5).

According to TSANIS et al., (2007), the index of short circuiting (I) expressing the amounts of water that flow very quickly to the outlet was defined as:

$$I = \frac{t_o}{t_n} \quad [-] \qquad (3.19)$$

Where t_o - time at which tracer first appeared

Sensitivity studies were carried out by changing the dominant parameters of the general case. The sensitivity studies in this work were with respect to:

1. Inlet design including inflow via a subsurface drainage pipe and surface drainage ditch.

2. Flood conditions (Q = 0.03 m^3/s).

3. Bottom friction including Manning roughness coefficient of the general case (n = 0.05 $s/m^{1/3}$) and 0.2 $s/m^{1/3}$ which considered the expected factors increasing the friction such as the low velocities, big plants and wind stress.

4. Viscosity and diffusivity of $\upsilon = \upsilon_t$ = 0.1 and 0.001 m^2/s.

Many scenarios were also undertaken which represented different configurations of baffles. Those configurations provided different numbers, widths and positions of baffles as shown in Figure (3.9).

All parameters being t_m, t_n, t_i, I and e were estimated for all the scenarios concerning dominant parameters and baffles' configurations.

The salt - removal efficiency of the pond for different baffles' scenarios were determined. t_m estimated from Eq. (3.18) was integrated with a first - order salt - removal kinetic reaction for duckweeds developed by OMAR and BALLA (2009) using the following formula:

$$\ln S = \ln S_o - K_r \times t_m \qquad (r^2 = 0.95) \tag{3.20}$$

Where S - the resultant outlet salinity [mg/l]

S_o - the initial salinity in the pond = 650 [mg/l]

K_r - first - order salt removal rate of duckweeds [1/d]

t_m - the mean residence time [d]

r - the correlation coefficient, and $r^2 = 0.95$ indicated a very good correlation

The values resulted from Eq. (3.20) were only used to compare relative changes in removal efficiency for the different scenarios of baffles. However, in practice many factors affect the removal such as temperature or existence of other plants that accumulate salts.

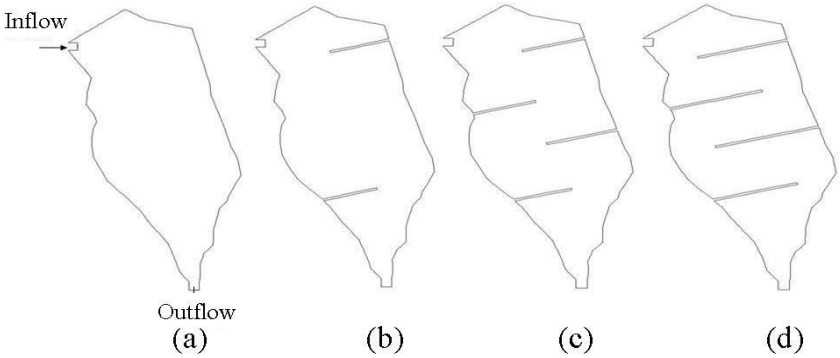

Figure 3.9: Un - baffled pond (a), pond with two baffles of 50 % width (b), four baffles of 50 % width (c), and four baffles of 70 % width (d)

3.4 Statistical methods

During the *Lemna* test with respect to salinity (Section 3.1.2), the influence of NaCl concentrations on both, duckweeds' growth parameters and removals of different elements have been statistically assessed. The Pearson's correlation coefficient (r) has been used to measure the strength of association between NaCl concentrations and both, duckweeds' growth parameters and removals of different elements.

The Pearson's correlation coefficient (r) is obtained for a series of n measurements of two groups of continuous variables (x_i and y_i) as shown in the formula below:

$$r = \frac{1}{(n-1)} \sum_{i=1}^{n} \frac{(x_i - \bar{x})(y_i - \bar{y})}{s_x s_y} \tag{3.21}$$

Where $\bar{x}$ - the mean value of variable x_i

$\bar{y}$ - the mean value of variable y_i

s_x, s_y - the standard deviations of variables x_i and y_i which are defined below:

$$s_x = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{3.22}$$

$$s_y = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{3.23}$$

The significance of correlation between NaCl concentrations and both, duckweeds' growth parameters and removals of different elements was evaluated using the hypothesis test. HELSEL and HIRSCH, (1992) explained the hypothesis test as: When p - value < α - level, H_0 is rejected, where:

H_0 - the null hypothesis that states the null situation (no difference between groups, no relation between variables)

α - the significance level or the probability of incorrectly rejecting the null hypothesis (the statistical tradition uses a default of 5 % (0.05))

p - the probability of obtaining the computed test statistic or the significance level attained by data

The smaller the p - value, the less likely the observed test statistic is when H_0 is true, and the stronger the evidence for rejection of the null hypothesis.

In conclusion, when $p < 0.05$, the correlation between two continuous variables is significant either positively if $r < 0$, or negatively if $r > 0$.

During the logistic growth model test for *Lemna minor* (Section 3.1.3), the confidence interval has been estimated for the carrying capacities (K) and the intrinsic rates of growth (r_g). The confidence interval is a range about the mean which has a stated probability of containing the true value. The confidence interval (CI) is computed as:

$$CI = 1 - \alpha \tag{3.24}$$

Where α - the significance level or the probability that the interval will not cover the true value = 5 % (0.05)

Therefore, a 95 % confidence interval has been used in this study. According to HELSEL and HIRSCH, (1992), the 95 % confidence interval (CI) is computed as:

$$CI = t_{(\alpha/2,n-1)} \times \sqrt{s^2/n} \tag{3.25}$$

Where $t_{(\alpha/2,n-1)}$ - a statistical parameter which is obtained from a table and varies with the percent probability (here 5 %) and the number of replicates examined

s - the standard deviation

The true mean values in the logistic growth model test are shown as the mean values ± CI.

During the investigations under natural conditions (Section 3.2.2), the salt - removal reaction of duckweeds has been analyzed. The integral method has

been used according to CHAPRA, (1997) to determine whether the salt - removal kinetics' reaction was zero -, first -, or second - order.

For zero - order reaction, plotting salt mass (SM) versus time (t) should yield a straight line. For the first - order reaction, plotting ln SM versus t should yield a straight line. For the second - order reaction, plotting 1/SM versus t should yield a straight line. Each plot includes the best - fit line developed with the linear regression.

R - squared (r^2) has been used for statistically measuring how well a regression line approximated the data points of SM, ln SM and 1/SM in the investigations under natural conditions. r^2 is simply the square of the Pearson's correlation coefficient (r) obtained from Eq. (3.21).

Excel has been used in this work for:

1. Plotting the data and add a trend - line.
2. Calculation of the standard deviation (s), correlation coefficient (r) and, subsequently (r^2).

The p - value for significance has been determined using the software program (Statistics Calculator, Version 2).

4 Results and discussion

4.1 Investigations under controlled climate conditions

4.1.1 Effect of salinity on duckweeds' growth

Tests (1), (2), (3), (4), (5) and (6) have been undertaken under different NaCl concentrations and temperatures. Tests (1) and (2) were under NaCl concentrations from 0 to 10000 mg/l and temperature 25 ºC. Tests (3) and (4) were under NaCl concentrations from 0 to 500 mg/l and temperature 25 ºC. Test (5) was under NaCl concentrations from 0 to 10000 mg/l and temperature 35 ºC. Test (6) was under NaCl concentrations from 0 to 500 mg/l and temperature 35 ºC.

In test (1), a positive significant correlation was noticed between NaCl concentrations and growth inhibition of fronds' count (I_r) where $r = 0.85$, $p < 0.05$. A positive significant correlation was also noticed between NaCl concentrations and growth inhibition of dry biomass (I_b) where $r = 0.87$, $p < 0.05$ (Figure 4.1). The no observed effect concentration (NOEC), low observed effect concentration (LOEC) and the concentration which caused 50 % of growth inhibition (EC_{50}) were 0.5, 1 and 1.8 g/l respectively for I_r and 0.5, 1 and 1.6 g/l respectively for I_b. For both concentrations 500 and 1000 mg/l, the inhibition growth rate had a negative sign compared to zero - concentration.

Results of test (2) showed a strong positive significant correlation for I_r (where $r = 0.92$, $p < 0.01$) and I_b (where $r = 0.99$, $p < 0.01$) (Figure 4.2). The NOEC, LOEC and EC_{50} were 0.5, 1 and 1.5 g/l respectively for I_r and 0.5, 1 and 1.3 g/l respectively for I_b. For concentration 500 mg/l, it was also found that the inhibition growth rate compared to zero - concentration had a negative sign.

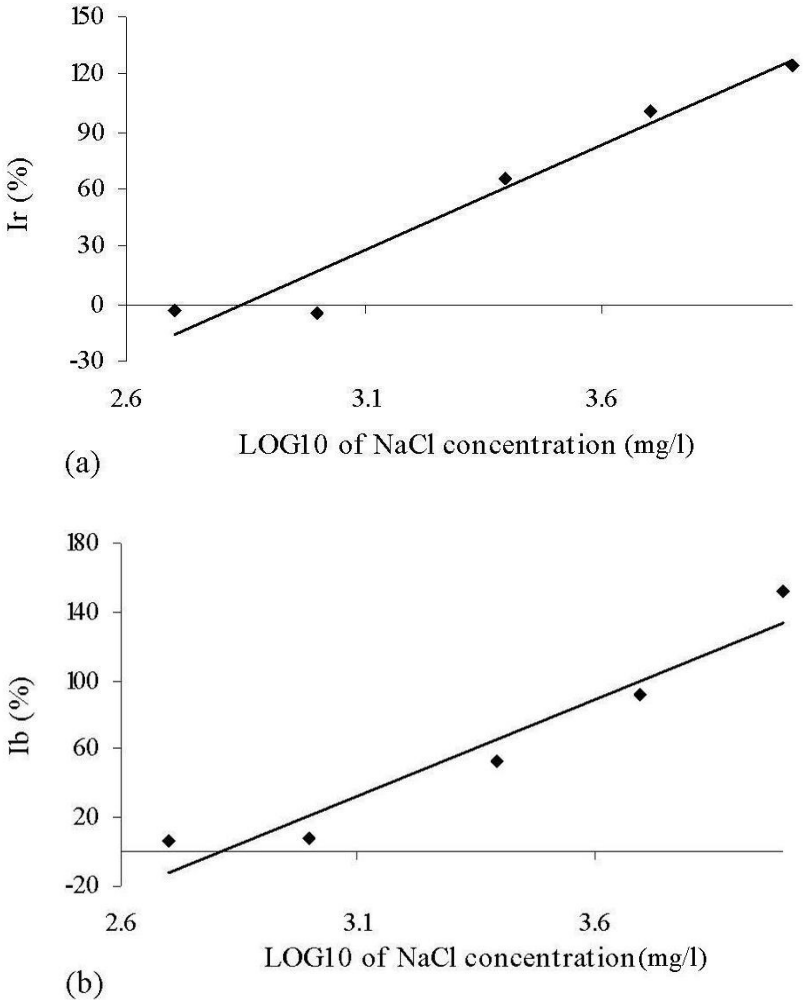

Figure 4.1: Influence of NaCl concentrations from 0 - 10000 mg/l on growth inhibition of frond count (a) and dry biomass (b) at temperature 25 ºC in test (1)

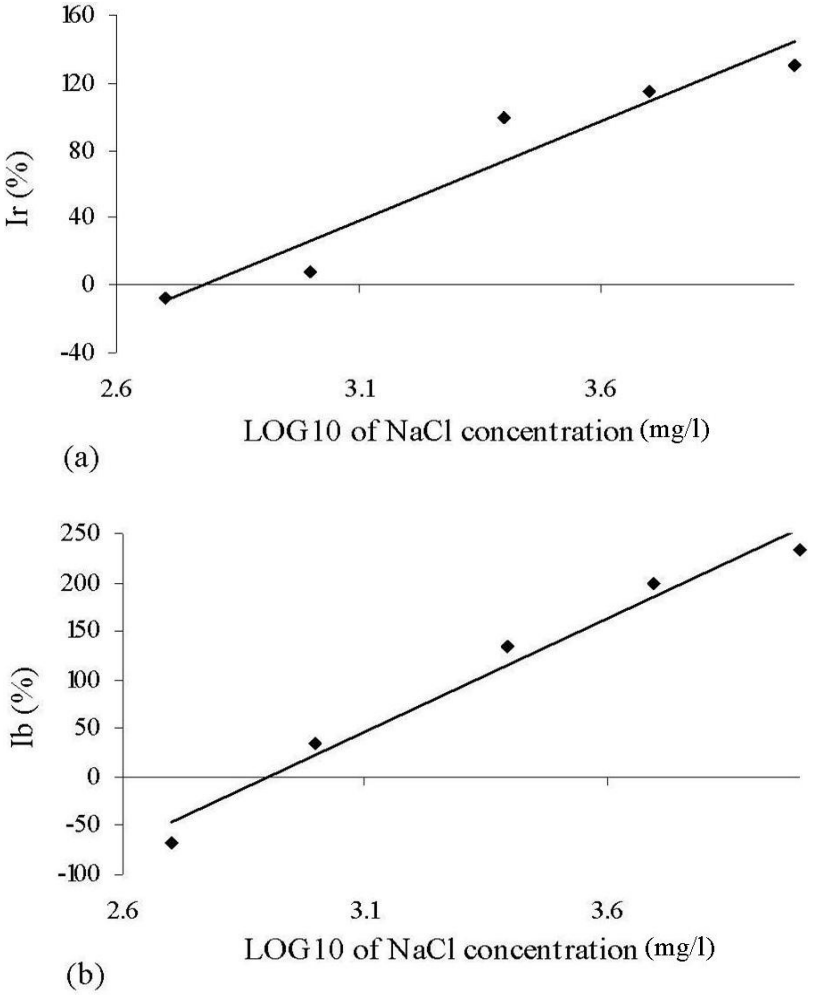

Figure 4.2: Influence of NaCl concentrations from 0 - 10000 mg/l on growth inhibition of frond count (a) and dry biomass (b) at temperature 25 ºC in test (2)

By increasing NaCl concentrations the duckweed growth parameters such as dry weight (D.W) and specific growth rate (μ) decreased significantly in tests (1) and (2) ($p < 0.05$) (Table 4.1 and Table 4.2). But, an increase in growth parameters was found at low salinities (500 mg/l in test (1) and up to 1000 mg/l in test (2)).

Table 4.1: Test (1): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 10000 mg/l and temperature 25ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	$\overline{D.W} \pm s$ (g)
0	380	38.4 ± 1.18	0.0045 ± 0.001
500 NOEC	1297	41.2 ± 1.208	0.0055 ± 0.001
1000 LOEC	1862	35.5 ± 1.071	0.004 ± 0.0008
2500	3612	0 ± 0	0.0025 ± 0.0006
5000	6447	-5.6 ± 2.5	0.0015 ± 0.001
10000	11571	-11.9 ± 4.112	0.001 ± 0

Table 4.2: Test (2): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 10000 mg/l and temperature 25 ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	$\overline{D.W} \pm s$ (g)
0	205	30.655 ± 1.158	0.0256 ± 0.004
500 NOEC	844	32.20 ± 1.602	0.0223 ± 0.003
1000 LOEC	1456	32.051 ± 1.112	0.0223 ± 0.006
2500	3129	10.496 ± 1.245	0.0083 ± 0.0005
5000	5873	-0.453 ± 0.785	0.0036 ± 0.0005
10000	11221	-7.42 ± 6.595	0.001 ± 0

Colour of all fronds at concentration 0 and 500 mg/l was green. Few brown fronds were found at 1000 mg/l and increased at 2500 mg/l. Most fronds were necrosis at 5000 mg/l. All fronds were almost necrosis and many roots decayed and the fronds separated from each other at 10000 mg/l (Figure 4.3).

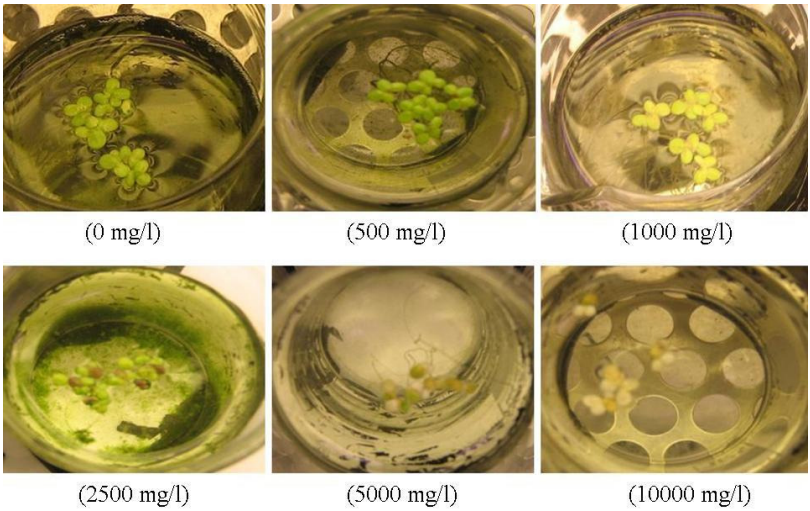

Figure 4.3: *Lemna minor* features under different NaCl concentrations in tests (1) and (2)

Under a low range of NaCl concentrations from 0 - 500 mg/l and a temperature 25 ºC in tests (3) and (4), EC_{50} laid outside the concentrations range. Unlike the previous results, there was no significant correlation ($p > 0.05$) between NaCl concentrations and growth parameters. Therefore, values of I_r and I_b are shown in Table 4.3) and Table 4.4) and not in figures. It was noticed that at all concentrations, I_r and I_b were negative and the dry weight, fronds' count and specific growth rate (μ) were higher than those at control.

Table 4.3: Test (3): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 500 mg/l and temperature 25 ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	I_r (%)	$\overline{D.W} \pm s$ (g)	I_b (%)
0	203	38.4 ± 1.18		0.0045 ± 0.001	
20	224	43.9 ± 1.5	-14.1	0.0065 ± 0.003	-133.3
80	300	41.2 ± 1.125	-7.2	0.0055 ± 0.002	-66.7
150	394	43.9 ± 1.412	-14.1	0.007 ± 0.003	-166.7
250	521	41.2 ± 1.2	-7.2	0.0055 ± 0.003	-66.7
500	840	41.2 ± 1.208	-7.2	0.0055 ± 0.001	-66.7

Table 4.4: Test (4): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 500 mg/l and temperature 25 ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	I_r (%)	$\overline{D.W} \pm s$ (g)	I_b (%)
0	205	30.6 ± 1.15		0.0256 ± 0.004	
20	238	31.7 ± 1.47	-3.4	0.028 ± 0.006	-3.63
80	315	30.1 ± 0.67	1.6	0.0206 ± 0.002	9.95
150	410	33.1 ± 2.52	-7.7	0.033 ± 0.004	-11.84
250	519	31.5 ± 2.82	-2.8	0.025 ± 0.007	1.99
500	844	32.1 ± 1.61	-4.4	0.0223 ± 0.003	6.42

Colour of all fronds was found green at all NaCl concentrations in tests (3) and (4). No decay or separation between fronds and roots was found (Figure 4.4).

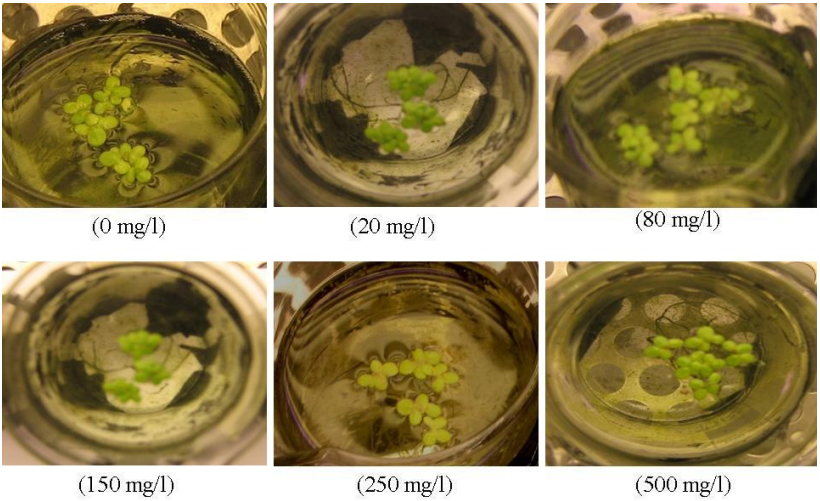

Figure 4.4: *Lemna minor* features under different NaCl concentrations in tests (3) and (4)

In conclusion, results of *Lemna* tests prove that the *Lemna minor* growth is being inhibited when NaCl concentrations increase in the range from 0 - 10000 mg/l (total salinity from 0.2 - 11.5 g/l). In addition, by increasing NaCl concentrations all duckweed growth parameters such as dry weight, fronds' count and specific growth rate (μ) decreased significantly ($p < 0.05$) in tests (1) and (2) (Table 4.1 and Table 4.2). But, an increase in growth parameters was found at low salinities (500 mg/l in test (1) and up to 1000 mg/l in test (2)). However, the growth is independent on NaCl concentrations in the range from 0 - 500 mg/l (total salinity from 0.2 - 0.8 g/l). Moreover, low salinity promotes the *Lemna minor* growth and this has been proved due to:

i) The observed higher growth parameters at all NaCl concentrations up to 1000 mg/l compared to those at zero - concentration.

ii) The observed negative values of growth inhibition rates at concentrations up to 1000 mg/l.

For understanding how the growth rate changed over time, growth data were obtained every two days for each NaCl concentration. The intrinsic growth rate (r_g) was estimated in the period of time in which the maximum change in frond number per day per frond occurred.

For example, at concentration 0 mg/l (Table 4.5) the frond number increased from 11 fronds on day 4 to 22 fronds on day 6. The change in frond number per day was 5.5 and the change in frond number per day per frond was obtained as 5.5 ÷ 22 = 0.25 being the maximum value. Therefore, the intrinsic rate of growth at concentration 0 mg/l was estimated for the period from day 4 to 6.

Table 4.5: *Lemna minor* growth data over time at NaCl concentration 0 mg/l

Day	Frond number	Change in frond number	Change in frond number/day	Change in frond number/day/frond
0	6	-	-	-
2	8	2	1	0.125
4	11	3	1.5	0.136
6	22	11	5.5	0.25
8	27	5	2.5	0.092
10	32	5	2.5	0.078
12	37	5	2.5	0.067
14	40	3	1.5	0.037
16	41	1	0.5	0.012
18	41	0	0	0

Using the exponential growth formula in Eq. (3.4) where $N_t = 22$, $N_o = 11$, and t = 2 days, the intrinsic rate of growth (r_g) = 34.6 % per day. Similarly, r_g was obtained for all NaCl concentrations. Table (4.6) shows mean values of (r_g) and carrying capacities (KC) at which the growth rate slowed to almost zero. *Lemna minor* reached its KC after the same period of time for all NaCl concentrations.

Figure (4.5) shows how the *Lemna minor* growth changed over time under different NaCl concentrations. The maximum growth rate as well as the maximum KC (44 fronds) were noticed at NaCl concentration 250 mg/l. NaCl concentrations from 0 - 1000 mg/l (total salinity from 0.2 - 1.5 g/l) did not make observable changes in *Lemna minor* growth with maximum growth rate at concentration 2500 mg/l (total salinity = 0.52 g/l). Above NaCl concentration 2500 mg/l (total salinity = 3.1 g/l), the growth decreased severely.

Table 4.6: Mean values $\overline{KC}$ and $\overline{r_g}$ for *Lemna minor* with their 95% CI

NaCl (mg/l)	Salinity (mg/l)	$\overline{KC} \pm CI$ (frond)	$\overline{r_g} \pm CI$ (%)
0	205	41 ± 1.4	0.346 ± 0.08
20	238	38 ± 1.4	0.273 ± 0.03
80	315	34 ± 0	0.242 ± 0.05
150	410	36 ± 1.4	0.229 ± 0.06
250	519	44 ± 1.4	0.346 ± 0.02
500	844	42 ± 0	0.323 ± 0.05
1000	1456	38 ± 0	0.32 ± 0.03
2500	3129	23 ± 0	0.168 ± 0.02
5000	5873	6 ± 0	0 ± 0
10000	11221	6 ± 0	0 ± 0

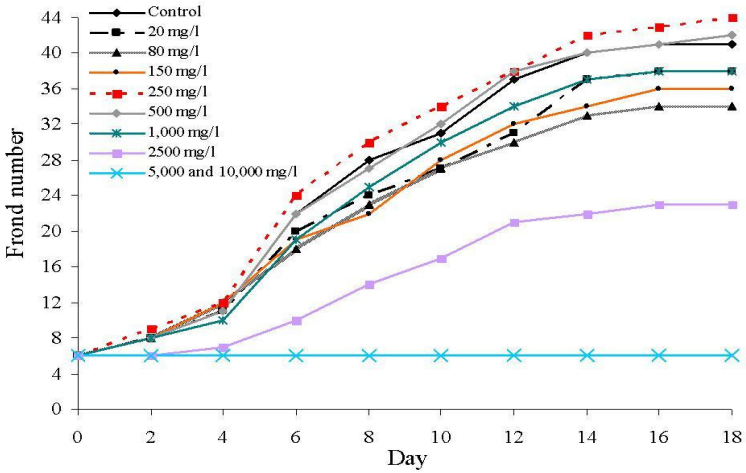

Figure 4.5: *Lemna minor* frond number (growth change) over time under NaCl concentrations

The conclusion of all investigations under controlled climate conditions with respect to growth is:

- Duckweeds' growth is promoted at low salinity up to NaCl concentration 500 mg/l (total salinity = 1.3 g/l).
- Duckweeds' growth is not affected up to concentration 1000 mg/l (total salinity = 1.5 g/l).
- Above concentration 1000 mg/l (total salinity = 1.5 g/l), the duckweed growth is being inhibited gradually.
- Above concentration 2500 mg/l (total salinity = 3.1 g/l), duckweeds can not survive. This result agrees with JOURNEY, (1991) who reported duckweeds' tolerance to relatively high salts' concentrations up to about 4 g/l.

The present study reports low EC_{50} values of dry biomass ranging from 1.3 to 1.7 g/l compared to BUCKLEY et al., (1996) who recorded EC_{50} values from 4.8 to 5.5 g/l. BUCKLEY et al., (1996) tested NaCl concentrations of 0, 2.5, 4.3, 7.2 and 12 g/l and showed that the NaCl increase reduced the growth rate. This result is in agreement with the present study for concentrations from 0 - 10 g/l, but in disagreement for concentrations from 0 - 0.5 g/l. This disagreement may exist because the previous study investigated the *Lemna minor* response to concentrations above 2.5 g/l and has not considered any low concentrations.

4.1.2 Effect of temperature on duckweed growth

Similarly, at temperature 35 ºC the *Lemna minor* growth parameters were influenced by the same way. In test (5) under NaCl concentrations from 0 - 10000 mg/l and temperature 35 ºC, a positive significant correlation was noticed between NaCl concentrations and both I_r ($r = 0.87$, $p < 0.05$) and I_b ($r = 0.94$, $p < 0.01$) (Figure 4.6).

The NOEC, LOEC and EC_{50} were 0.5, 1 and 2.2 g/l respectively for I_r and 0.5, 1 and 1.7 g/l respectively for I_b. The growth parameters under different NaCl concentrations at temperature 35ºC were less than those at temperature 25ºC (Table 4.7 and Table 4.8).

For low range of NaCl concentrations from 0 - 500 mg/l in test (6), EC_{50} laid outside the concentrations range. No significant correlation ($p > 0.05$) was found between NaCl concentrations and growth parameters (Table 4.8). No significant correlation ($p > 0.05$) was also found between NaCl concentrations and both, I_b and I_r. Therefore, values of I_r and I_b are shown in Table (4.8) and not in figures. At all concentrations, I_r and I_b were negative. The dry weight, frond number and specific growth rate (μ) were greater than those at control.

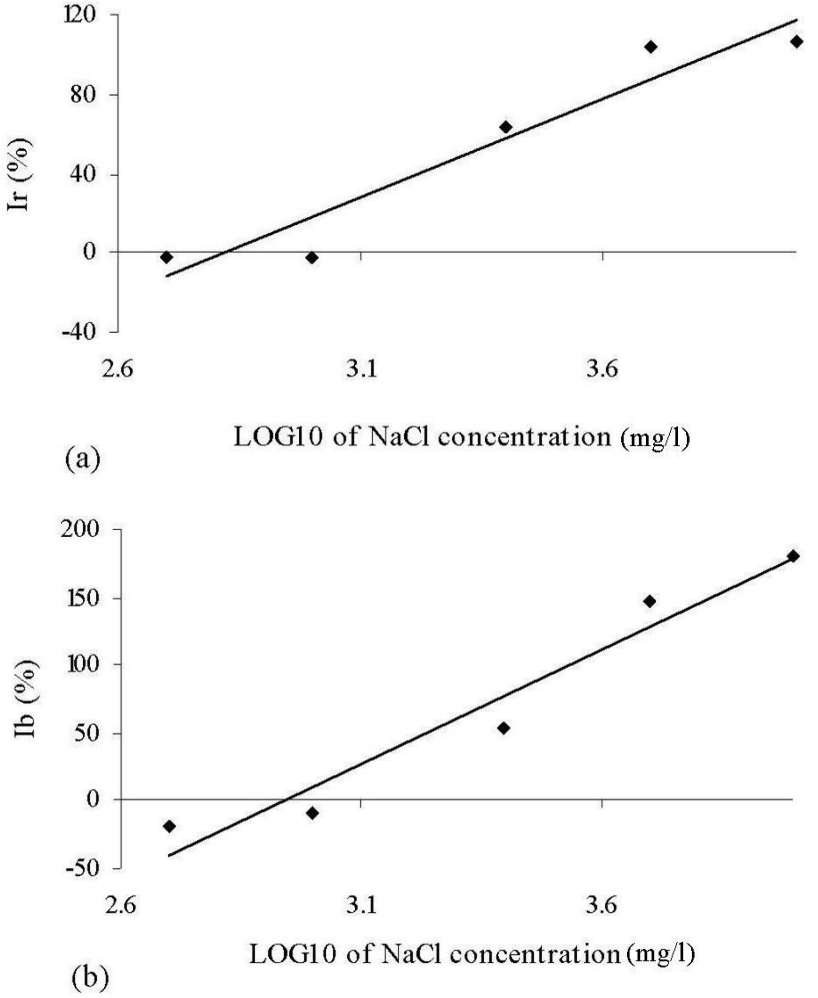

Figure 4.6: Influence of NaCl concentrations from 0 - 10000 mg/l on growth inhibition of frond count (a) and dry biomass (b) at temperature 35 ºC in test (5)

Table 4.7: Test (5): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 10000 mg/l and temperature 35 ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	$\overline{D.W} \pm s$ (g)
0	205	23.33±0.003	0.0116±0.0005
500 NOEC	844	24.21±0.009	0.015±0.0025
1000 LOEC	1456	23.9±0.006	0.0133±0.0011
2500	3129	8.35±0.014	0.0056±0.0005
5000	5873	-0.92±0.007	0.0016±0.0005
10000	11221	-1.41±0.014	0±0

Table 4.8: Test (6): Mean values and standard deviations (s) of growth parameters under NaCl concentrations from 0 - 500 mg/l and temperature 35 ºC. Initial dry weight = 0.003 g

NaCl (mg/l)	Salinity (mg/l)	$\overline{\mu} \pm s$ (%)	I_r (%)	$\overline{D.W} \pm s$ (g)	I_b (%)
0	205	0.233±0.003	-1.029	0.0116±0.0005	
20	238	0.235±0.007	-2.137	0.0136±0.0015	-11.402
80	315	0.238±0.003	-4.474	0.0136±0.0025	-10.85
150	410	0.243±0.008	-1.758	0.015±0.0026	-17.755
250	519	0.237±0.006	-3.785	0.014±0.001	-13.368
500	844	0.242±0.009	-1.029	0.0153±0.002	-19.666

From Figure 4.7, it is obvious that growth rates of *Lemna minor* at temperature 25ºC exceeded those at temperature 35ºC at all NaCl concentrations. At temperature 5 ºC, the intrinsic rate of increase was zero at all NaCl concentrations and no growth or inhibition was noticed. However, *Lemna minor* features indicated healthy conditions since the fronds were green and the roots did not separate from the fronds even at high concentrations (5000 and 10000 mg/l).

It was also found that no NaCl concentrations in the range from 0 to 10000 mg/l made an observable difference in the *Lemna minor* growth rate. Above this threshold concentration (NaCl = 1000 mg/l or total salinity = 1.5 g/l), a severe decrease in growth rate was found. Therefore, Figure 4.6 insures the previous results in section 4.1.1 being NaCl concentrations up to 1000 mg/l (total salinity = 1.5 g/l) have no influence on duckweeds' growth.

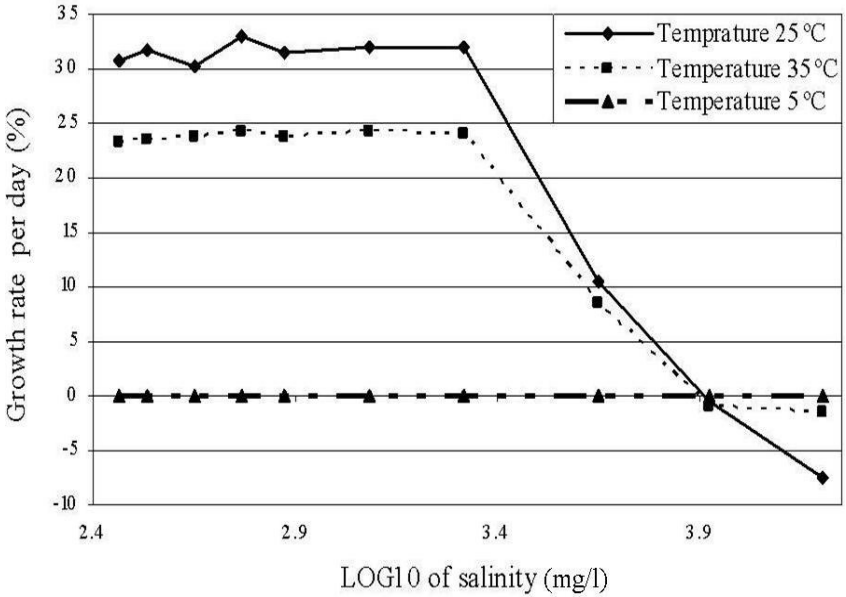

Figure 4.7: Growth of *Lemna minor* at different salinities and temperatures

The temperature's influence on the duckweeds' growth can be concluded as following:

- The optimal growth of duckweeds is achieved at temperature 25 ºC and decreases at temperature 35 ºC.
- At cold conditions (here 5 ºC), duckweeds' growth rate neither increases nor decreases but duckweeds keep their healthy features.

4.2 Uptake of salt, anions and cations

Depending on differences between initial and final concentrations for different solutions, the removal efficiency of salt, Ca^{+2}, K^{+}, Mg^{+}, and NO_3^- has been calculated. Desalination was up to 10.2 and 8.5 % of the initial salinity in one week at temperatures 25 and 35 ºC respectively, independent ($p > 0.05$) on salinity (Table 4.9, Table 4.10, Table 4.11 and Table 4.12).

Lemna minor has removed up to 83.5 % of the initial NO_3^-. A negative significant correlation [($r = -0.90$, $p < 0.05$), ($r = -0.89$, $p < 0.05$), ($r = -0.92$, $p < 0.05$)] has been found between salinity content and NO_3^- removal at all the tests under NaCl concentrations from 0 - 10,000 mg/l (Figure 4.8 and Figure 4.9). But no significance [($r = -0.64$, $p > 0.05$), ($r = -0.57$, $p > 0.05$), ($r = -0.68$, $p > 0.05$)] has been found at all the tests under NaCl concentrations from 0 - 500 mg/l (Table 4.11 and Table 4.12).

At temperature 35 ºC a lower NO_3^- removal was observed under different NaCl concentrations (Figure 4.8, Figure 4.9, Table 4.11 and Table 4.12).

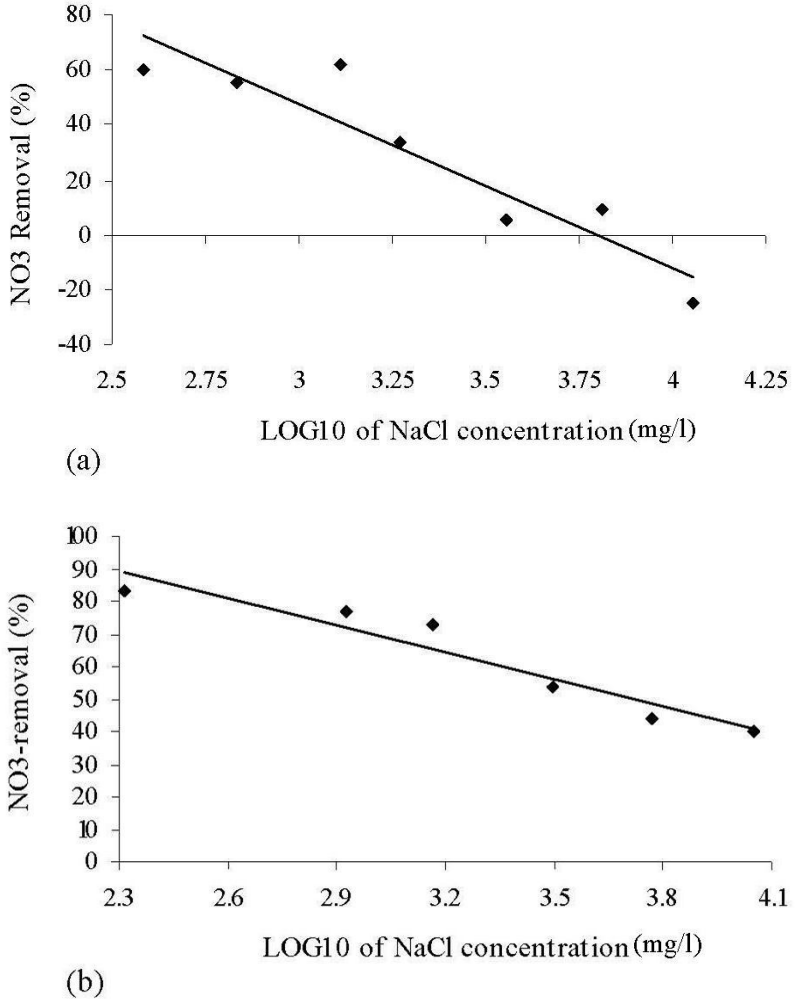

Figure 4.8: Influence of NaCl concentrations from 0 - 10000 mg/l on NO_3^- removal at temperature 25 ºC in test (1) (a) and test (2) (b)

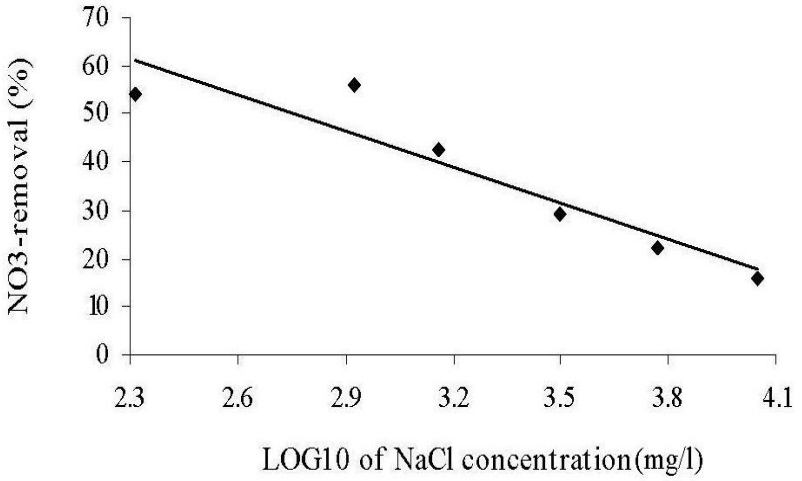

Figure 4.9: Influence of NaCl concentrations from 0 - 10000 mg/l on $NO3^-$ removal at temperature 35ºC in test (5)

Ca^{+2} removal was up to 73 %. Ca^{+2} removal decreased significantly [($r = -0.83$, $p < 0.05$), ($r = -0.85$, $p < 0.05$)] when salinity increased in tests (1) and (2) under NaCl concentrations from 0 - 10000 mg/l (Figure 4.10). Under NaCl concentrations from 0 - 500 mg/l a negative significant correlation was found ($r = -0.9$, $p < 0.05$) in test (3) (Figure 4.11), but no significance was found in test (4). Under temperature 35 ºC, no significance was observed neither from 0 - 500 mg/l in test (5) nor from 0 - 10000 mg/l in test (6) (Table 4.10 and Table 4.12).

Duckweeds removed different amounts of K^+ and Mg^+ independent on either NaCl concentrations or temperature. K^+ and Mg^+ removals were up to 83 and 94.9 respectively (Table 4.9, Table 4.10, Table 4.11 and Table 4.12).

Generally, reproducibility has shown results' similarities. However, there were few removal values which showed a very big difference after repeating the tests such as:

- At NaCl concentration 2500 mg /l, removal of K^+ was firstly 67 % (Table 4.9), but was 0 after the repetition (Table 4.10).
- At control (0 mg /l), removal of Ca^+ was firstly 47 % (Table 4.11), but was 0 after the repetition (Table 4.12).

As mentioned previously, that temperature might have influenced the removals, but the big difference might have been because of error in measurements.

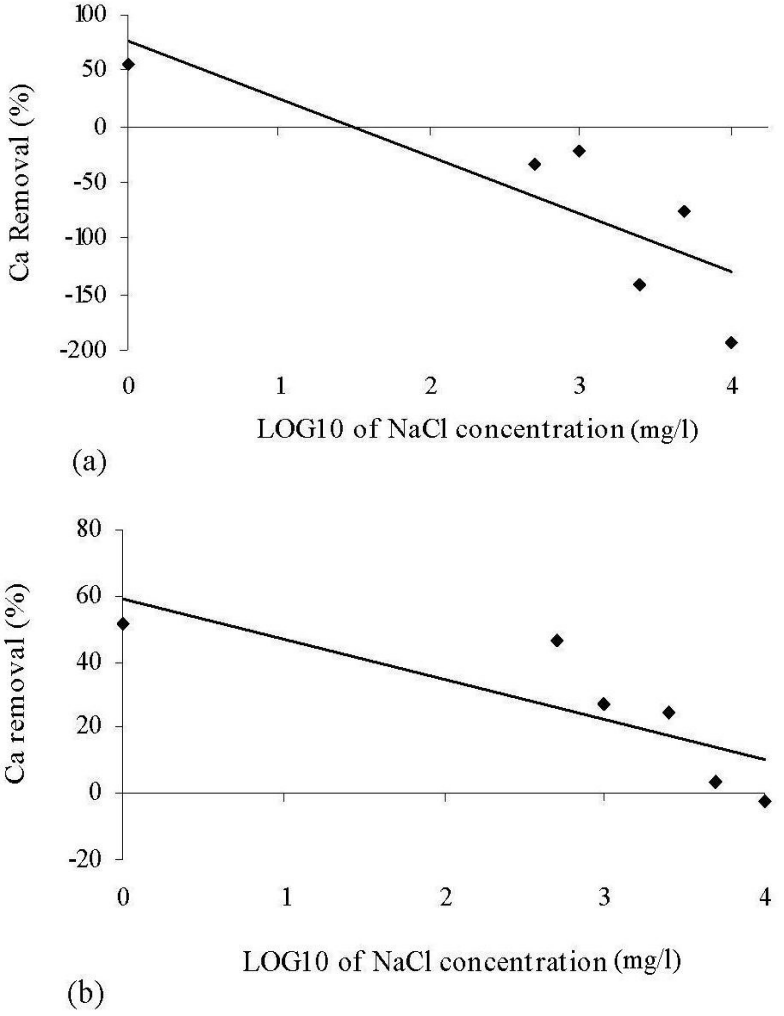

Figure 4.10: Ca^{+2} removal under NaCl concentrations from 0 - 10000 mg/l in tests (1) and (2)

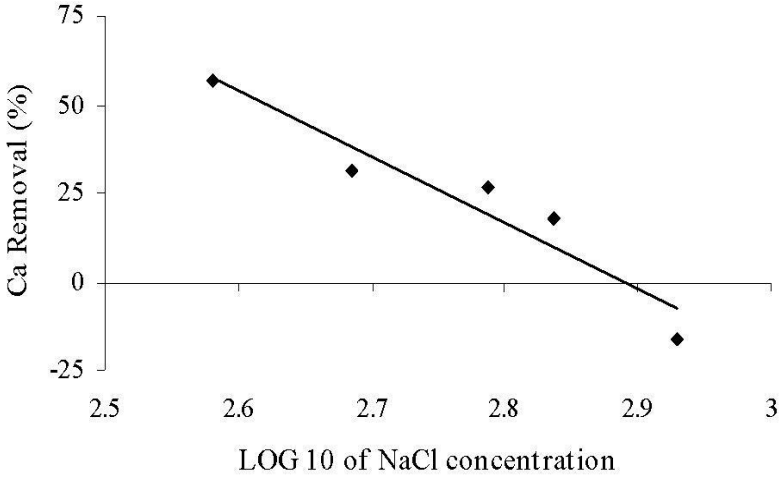

Figure 4.11: Ca^{+2} removal under NaCl concentrations from 0 - 500 mg/l in test (3)

Table 4.9: Removals of salinity, K^+ and Mg^+ under NaCl concentrations from 0 - 10000 mg/l and temperature 25 ºC in test (1)

NaCl Concentration (mg/l)	Salinity (%)	K^+ (%)	Mg^+ (%)
C	10.2	75	28.67
500	5	83	10.68
1000	3.6	78.76	7.76
2500	2	67	0.17
5000	2.4	82.5	2
10000	1.5	68.31	6

Table 4.10: Removals of salinity, Ca^{+2}, K^{+} and Mg^{+} under NaCl concentrations from 0 - 10000 mg/l and temperature 35 ºC in test (5)

NaCl Concentration (mg/l)	Salinity (%)	Ca^{+2} (%)	K^{+} (%)	Mg^{+} (%)
C	8.5	0	34.23	0
500	8	46.54	58.38	16.21
1000	1.7	26.92	55.22	14.89
2500	1.5	3.17	0	10
5000	2.1	24.55	51	6.19
10000	1	51.56	75.56	12.92

Table 4.11: Removals of salinity, Ca^{+2}, K^{+}, Mg^{+} and NO_3^{-} under NaCl concentrations from 0 - 500 mg/l and temperature 25 ºC in test (3)

NaCl Concentration (mg/l)	Salinity (%)	Ca^{+2} (%)	K^{+} (%)	Mg^{+} (%)	NO_3^{-} (%)
C	10.2	47.15	75.08	28.68	83.5
20	8.6	0.83	90.24	15.16	78.9
80	7.7	0	87.38	10.61	79.02
150	9	31.12	90.09	14.54	85.86
250	4.5	22.27	94.88	14.38	76.4
500	5	31.07	83.04	10.67	77

Table 4.12: Removals of salinity, Ca^{+2}, K^+, Mg^+ and NO_3^- under NaCl concentrations from 0 - 500 mg/l and temperature 35 ºC in test (6)

NaCl Concentration (mg/l)	Salinity (%)	Ca^2 (%)	K^+ (%)	Mg^+ (%)	NO_3^- (%)
C	8.5	0	34.23	0	53.91
20	6.76	0	36.73	0	46.17
80	4.44	7.35	49.93	6.22	46.22
150	8.55	21.92	48.6	13.45	68.45
250	2.83	36	83.81	21.22	61.03
500	8	46.54	58.38	16.21	56

The present study provides the first data on the influence of water salinity on removal of NO_3^-, Ca^{+2}, K^+ and Mg^+. Under controlled climate conditions, when NaCl concentration increases, the NO_3^- removal decreases, however, removal is independent on NaCl concentrations up to 0.5 g/l (total salinity = 1.3 g/l).

Ca^{+2} removal decreases when NaCl increases either for low range or high range of NaCl concentrations. Ca^{+2} removal is very sensitive to salinity even to low levels. This result agrees with the protective effect of Ca^+ against NaCl toxicity observed in many aquatic plants (ROUT, SHAW, 2000). *Lemna minor* removes K^+ and Mg^+ independent on water salinity.

The highest NO_3^- removals are achieved at temperature 25 ºC under different NaCl concentrations. Duckweeds can also remove Ca^{+2}, K^+, and Mg^+ from the water but not independent on temperature.

4.3 Investigations under natural climate conditions

4.3.1 Phase (1)

4.3.1.1 Effect of salinity on duckweeds' growth

In phase (1), experiments (1) and (2) have been carried out to investigate duckweeds in two containers with water salinities 0.5 and 1.25 g/l. In experiment (1), the final biomass and relative growth rate (RGR) of duckweeds by the end of week two under water salinities 0.5 and 1.25 g/l indicated a high growth rate in both containers for the first two weeks (Table 4.13). Observable higher values under lower water salinity were found. The growth continued in the next three weeks but growth parameters in both containers became almost equal. From week six up to the end, growth was found only under higher water salinity.

In experiment (2), the growth parameters increased in both containers with higher values in container (1) with lower water salinity. However, the growth parameters did not become equal in both containers until the end of week (7).

Table 4.13: Phase (1): Growth data of duckweeds. Initial biomass = 400 g

	Salinity = 0.5 g/l			Salinity = 1.25 g/l		
Experiment (1)	Final biomass (g)	RGR (%)	RGR (g/d)	Final biomass (g)	RGR (%)	RGR (g/d)
Week: 1 and 2	1675	319	98	1325	231	71
Week: 3, 4 and 5	970	143	25	930	133	23
Week: 6 and 7	385	-4	-1	420	8	2
Week: 8, 9 and 10	185	-54	-11	420	5	1
Experiment (2)						
Week: 1 and 2	1275	219	63	900	125	36
Week: 3, 4 and 5	1055	164	33	790	98	20
Week: 6 and 7	500	25	7	375	-31	-2

Under natural climate conditions, the investigations in phase (1) prove that the growth rate of duckweeds is less under higher salinity conditions in the first few weeks (Table 4.13). After a long period of time (six weeks), duckweeds adapt to the higher salinity and growth rate keeps increasing even more than those in the lower salinity. TKALEC et al., (2001) have also observed a long term adaptation during NaCl treatment.

4.3.1.2 Uptake of salts and nutrients

In phase (1), the daily salinity removal of duckweeds in both containers with water salinity = 0.5 g/l and 1.25 g/l was determined from Eq. (3.7). The daily salinity removal rate (A×J) was up to 26 and 42 g/d in container (1) and (2), respectively. The experiment (2) showed a daily salinity removal up to 48 and 65 g/d in containers (1) and (2), respectively. The resultant cumulative removal was 190 and 222 g in containers (1) and (2), respectively in the experiment (1) and 167 and 303 g in containers (1) and (2), respectively in the experiment (2) (Figure 4.12).

However, many negative removal values were observed in both experiments. Those negative values might have been because of:

1. Errors in measurements.
2. Ignoring some mass components.
3. Assuming some values to be zero such as transformation and sedimentation and in reality they may have values.

The modifications in phase (2) have considered all those possible errors and assumptions by using tanks with duckweeds and others without duckweeds.

The salinity (EC) of solution of initial duckweeds before exposure to drainage water was 2590 µS/cm. In experiment (2), the salinity of final duckweeds' solution increased in both containers after exposure to drainage water for a period of time as an indicator to salinity accumulation in duckweeds' tissue (Table 4.14). The solution salinity was the highest in the first two weeks. The duckweeds were transferred again to both containers after washing and their solution salinity was as equal to the initial salinity = 2590 µS/cm. The final solution salinity at the end of week (5) was less than the one at the end of week (2). The final solution salinity at the end of week (7) was also less than the one at the end of week (5).

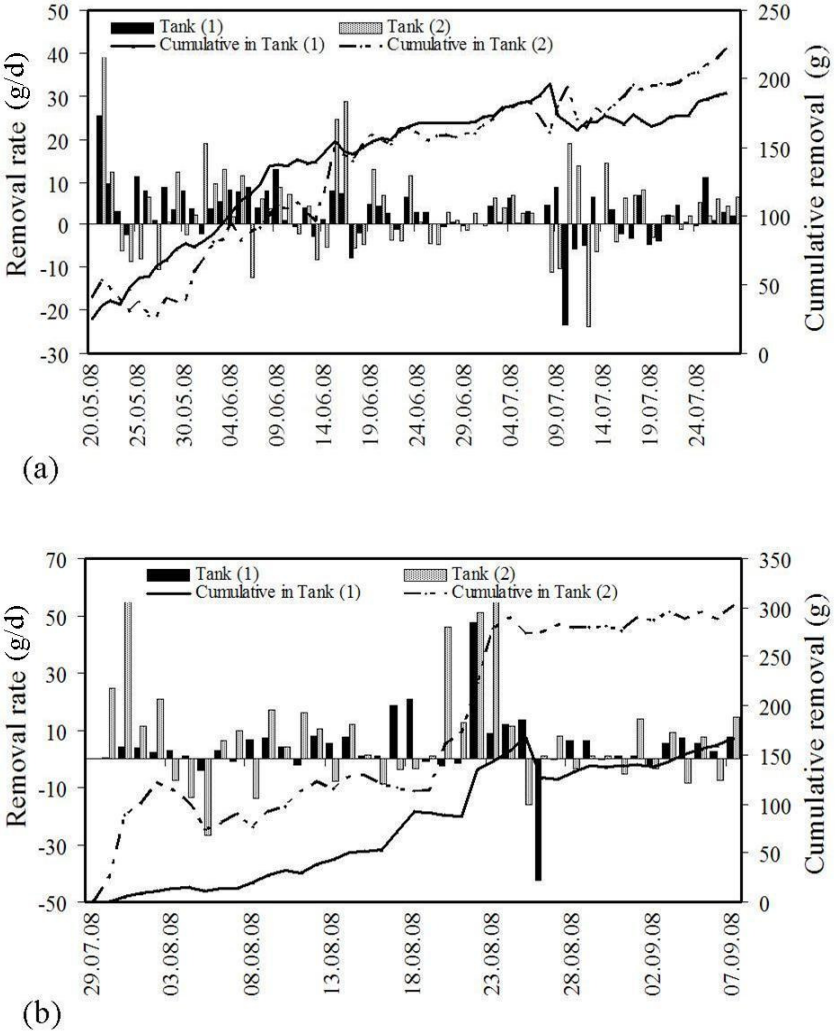

Figure 4.12: Daily salinity removal rate (A×J) and cumulative in two containers along experiment (1) (a) and experiment (2) (b)

Table 4.14: Electrical conductivity (EC) of duckweeds' solution in container (1) with water salinity = 0.5 and container (2) with water salinity = 1.25 g/l

Time	Container (1) EC (µS/cm)	Container (2) EC (µS/cm)
0	2590	
End of week (2)	5350	6520
End of week (5)	4610	4760
End of week (7)	2910	2930

The dry biomass analysis showed that duckweeds accumulated amounts of P and NO_3^- after their exposure to the water for two weeks. The accumulated values were higher in container (1) with lower salinity (Table 4.15).

Table 4.15: Dry biomass analysis for duckweeds exposed to water of salinities 0.5 g/l in container (1) and 1.25 g/l in container (2)

Parameter	Content (g) Initial	Content (g) Container (1)	Content (g) Container (2)	Accumulated (g) Container (1)	Accumulated (g) Container (2)
P^{-4}	0.315	2.672	2.357	2.357	1.843
NO_3^-	0.0015	0.104	0.046	0.102	0.044

4.3.2 Phase (2)

After results' analysis of phase (1), an experience has been gained concerning growth cycle, nutrient - demand, water depth and volume. Therefore, many modifications were carried out in phase (2). These modifications were chosen for many reasons:

- The initial water volume in the containers was big (1750 l) and the initial duckweeds' biomass was small (400 g). Subsequently, the salinity removal rates were small. Therefore, the big containers were replaced by small tanks in phase (2) what resulted in 20.5 l.
- Error in measurements or wrong assumptions in phase (1) that resulted in negative salt - removal rates have been eliminated in phase (2) by using tanks with duckweeds (duckweeds - covered tanks) and others without duckweeds (open - water tanks). Therefore, the difference between both, the salt - removal rate in duckweeds - covered tanks and open - water tanks was the actual and accurate salt - removal rate of duckweeds.
- Three different salinities were investigated in phase (2) instead of two salinities.

4.3.2.1 Effect of salinity on duckweeds' growth

Unlike phase (1), the growth parameters in phase (2) for salinities 0.6, 1.6 and 2.1 g/l indicated higher growth rates when salinity increased (Table 4.16). After repeating the experiment, the maximum growth rate was achieved in the water which had a middle salinity (1.6 g/l).

Table 4.16: Growth data of duckweeds in phase (2). Initial biomass = 50 g for experiment (1) and 30 g for experiment (2).

	Salinity = 0.6 g/l			Salinity = 1.6 g/l			Salinity = 2.1 g/l		
Experiment	Final biomass (g)	RGR (%)	RGR (g/d)	Final biomass (g)	RGR (%)	RGR (g/d)	Final biomass (g)	RGR (%)	RGR (g/d)
1	135	170	3.1	150	200	3.7	155	210	3.8
2	55	67	0.7	58	93	1	45	50	0.5

Investigations in phase (2) prove that the growth rate increases when salinity increases in the range from 0.6 to 2.1 g/l. In experiment (1) the maximum growth is achieved at the highest salinity being 2.1 g/l. However, in experiment (2) the maximum growth is achieved at salinity 1.6 g/l and not 2.1 g/l. Both experiments are in agreement that salinity 1.6 g/l promotes the growth, but in agreement concerning salinity 2.1 g/l.

The outdoor experiments under natural climate conditions either in phase (1) or (2) prove that duckweeds are not clearly affected by water salinity up to 2.1 g/l. But, it is clear that low salinity up to 1.6 g/l is stimulatory for growth.

4.3.2.2 Uptake of salts and nutrients

The salt - removal of duckweeds was calculated as the difference between salt - removal in both duckweed - covered and open - water tanks as in Eq. (3.10).

The integral method has been used according to CHAPRA, (1997) to determine whether the salt - removal kinetics' reaction was zero -, first -, or second - order for different salinities and different duckweeds' biomasses. Here, the salt masses (SM) were plotted.

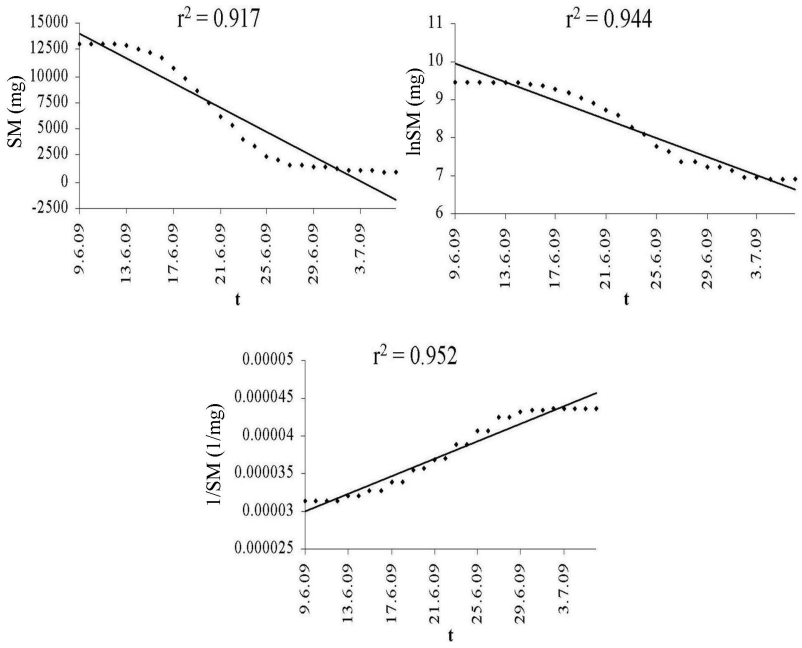

Figure 4.13: Plots to evaluate the reaction order for water salinity 0.6 g/l and duckweeds' biomass 50 g (intensity = 260 g/ m^2)

Figure (4.13) shows plots to evaluate the reaction order for salinity 0.6 g/l. The reaction was first - order since the plot of ln SM versus time (t) most closely approximated a straight line. The best - fit line was: ln SM = 9.944 - 0.122 × t (r^2 = 0.944). The rate of salt decrease was K_r = 0.122 d^{-1} or 12.2 % was lost in a day.

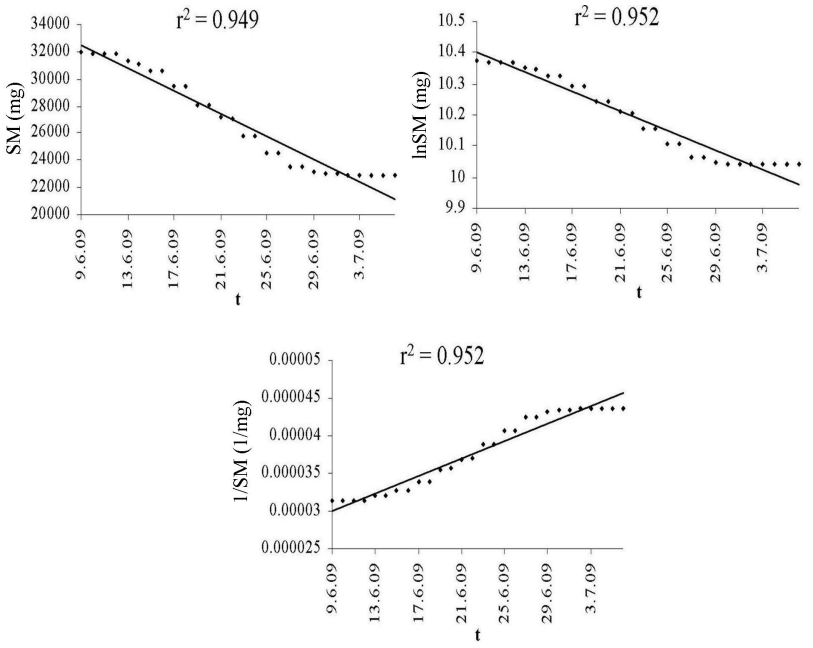

Figure 4.14: Plots to evaluate the reaction order for water salinity 1.6 g/l and duckweeds' biomass 50 g (intensity = 260 g/ m^2)

For salinity 1.6 g/l, clearly the plot of ln SM versus t most closely approximated a straight line (Figure 4.14). The best - fit line for this first - order reaction was:

$\ln SM = 10.4 - 0.015 \times t \quad (r^2 = 0.952)$

Therefore the rate of salt decrease was $K_r = 0.015\ d^{-1}$ or 1.5 % was lost a day.

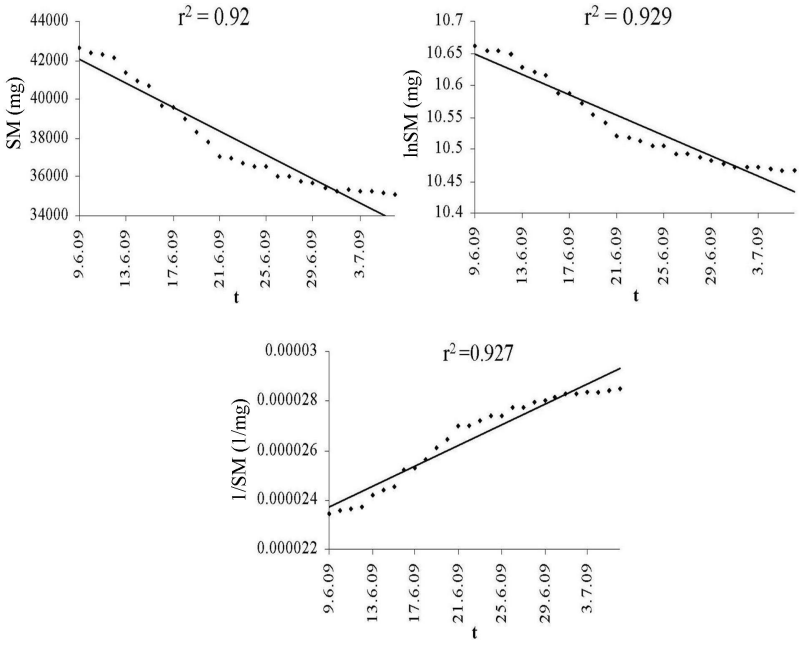

Figure 4.15: Plots to evaluate the reaction order for water salinity 2.1 g/l and duckweeds' biomass 50 g (intensity = 260 g/ m^2)

For salinity 2.1, the reaction was also first - order (Figure 4.15). The best - fit line was: ln SM = 10.648 - 0.008 × t (r^2 =0.929) with salt decrease rate K_r = 0.008 d^{-1}.

Similarly, the salinity - removal kinetics reactions have been determined for the same three salinities but with initial duckweeds' biomass of 30 g (intensity = 160 g/ m^2) and the results were as follows:

For salinity (0.6 g/l), the best - fit line was:

$S = 9.62 - 0.04 \times t$ ($r^2 = 0.96$) and the rate of salt decrease was $K_r = 0.04\ d^{-1}$.

- For salinity 1.6 g/l, the best - fit line was:

$S = 10.38 - 0.005 \times t$ ($r^2 = 0.96$) and the rate of decrease was $K_r = 0.005\ d^{-1}$.

- For salinity 2.1 g/l, the best - fit line was:

$S = 10.63 - 0.005 \times t$ ($r^2 = 0.96$) and the rate of decrease was $K_r = 0.014\ d^{-1}$.

Duckweeds' biomass to salt - mass coefficient (K_{ds}) was calculated in both experiments for all water salinities (Figure 4.16). It was observed that when K_{ds} coefficient decreased, the first-order salinity removal rate (K_r) decreased for salinity 0.6 and 1.6 g/l, and increased for salinity 2.1 g/l. The increase occurred for salinity 2.1 g/l can be ignored since it was too small. Water temperature in the period of time when experiments (1) and (2) were undertaken was between 15 - 32 ºC.

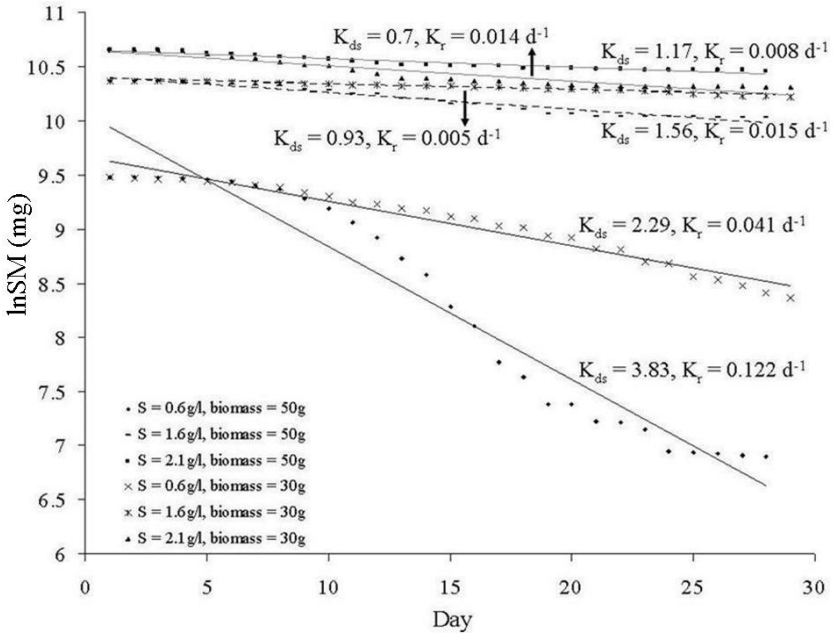

Figure 4.16: Plots of best - fit line for first - order reaction as well as salt removal rate (K_r) and ratio between duckweed biomass to water salinity (K_{ds})

The daily salt - mass removal was found up to 1350, 1321, and 1063 mg for water salinity 0.6, 1.6, and 2.1 g/l respectively in experiment (1) with initial duckweeds' intensity of 260 g/m^2 (Figure 4.17). At the end of this experiment it was found that the total salt - mass removed from the water of salinities with 0.6, 1.6 and 2.1 g/l was 12059, 9092, and 7556 mg in four weeks respectively and that means 92 %, 28.5 %, and 17.7 % of the initial salt - mass respectively.

The daily salt - mass removal was up to 703, 392, and 870 mg for salinity 0.6, 1.6, and 2.1 g/l respectively in experiment (2) with initial duckweeds' intensity of 160 g/m^2 (Figure 4.17). At the end of this experiment it was found that the totally removed salt - mass from the water of salinities 0.6, 1.6 and 2.1 g/l was

8751.374, 4480.386, and 9586.122 mg in four weeks respectively and that means 67 %, 14 %, and 22 % of the initial salt - mass respectively.

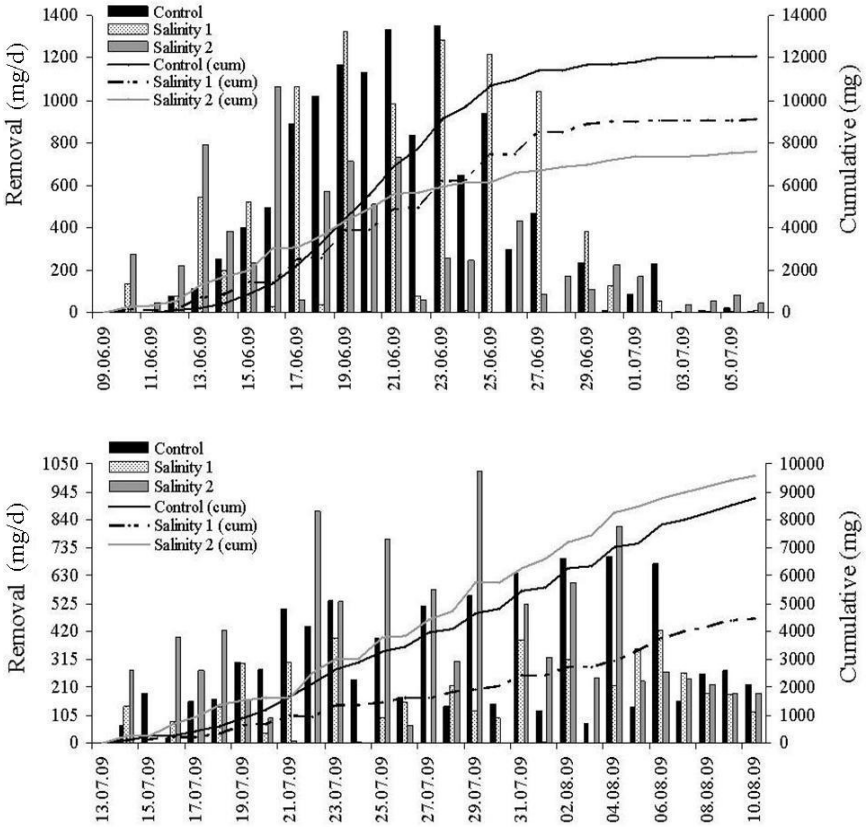

Figure 4.17: Daily and cumulative salinity removal for experiment (1) (up) and experiment (2) (down)

Depending on the difference between initial and final concentration, it was found that duckweeds removed up to 80.5 % of the initial NO_3^- in experiment

(1) and up to 73.5 % in experiment (2) in four weeks (Table 4.17 and Table 4.18). It is very clear that removal rates were higher in experiment (1) in which higher duckweeds' biomass was used. In each experiment, a decrease in NO_3^- removal rates was observed when salinity increased.

Removal of K^+ was high at salinity 0.6 g/l and decreased severely at salinity 1.6 and 2.1 g/l. The removal rates of other parameters were independent on salinity.

The dry biomass analysis showed that duckweeds accumulated amounts of N^{-3}, NO_3^-, Na^+, Cl^-, and NH_4^- in their tissue after their exposure to drainage water with three different salinities for four weeks (Table 4.19). The accumulated amounts of Na^+, Cl^-, and N^{-3} increased when the initial salinity in water increased. The accumulated amount of P^{-4} and NH_4^- decreased when salinity increased. The accumulated amount of NO_3^- was almost equal for all salinities.

Table 4.17: Removal of different parameters in experiment (1)

Salinity (g/l)	K^+ (%)	Mg^+ (%)	NO_3^- (%)
0.6	91	15.3	80.5
1.6	24	9.9	75.5
2.1	26.7	15.5	74

Table 4.18: Removal of different parameters in experiment (2)

Salinity (g/l)	Ca^{+2} (%)	P^{-4} (%)	NO_3^- (%)
0.6	8	40.5	73.5
1.6	14.5	13	58
2.1	6.5	7.6	39.5

Table 4.19: Dry biomass analysis presenting the accumulated parameters in duckweed tissue under different salinities (EC = 0.6, 1.6 and 2.1 g/l)

Parameter	Content (g)				Accumualted (g)		
	Initial	EC=0.6 g/l	EC=1.6 g/l	EC=2.1 g/l	EC=0.6 g/l	EC=1.6 g/l	EC=2.1 g/l
N^{-3}	19.14	46.55	48.52	51.72	27.41	29.38	32.58
P^{-4}	4.48	2.86	2.93	3.36	1.62	1.55	1.12
NO_3^-	0	0.19	0	0.21	0.2	0.22	0.21
Na^+	5.02	9.52	25.49	33.65	4.51	20.47	28.63
Cl^-	13.44	26.03	34.90	39.28	12.58	21.45	25.83
NH_4^-	0.22	1.06	1.01	1.01	0.84	0.79	0.79

The results of phase (2) prove that the salt - removal of duckweeds is first - order reaction kinetics under natural climate conditions. The first - order salt - removal depends mainly on the ratio between duckweeds' biomass and water salinity. The daily first-order removal in this study is between 0.5 and 12.2 % per day in water with temperatures between 15 - 32 ºC. Higher duckweeds' biomass (duckweeds' intensity = 260 g/m^2) achieves higher salt - removal. Duckweeds accumulate salts in their tissues and subsequently can desalinate the water.

In addition, duckweeds remove Na^+, K^+, Mg^+, Ca^{+2}, N^{-3}, NH_4^-, NO_3^- and Cl^-. Similar to the controlled climate investigations, NO_3^- removal decreases when salinity increases. Higher duckweed biomass increases the removal of NO_3^-. Unlike the controlled climate investigations, Ca^{+2} removal is independent on water salinity. Removal of K^+ and P^{-4} decreases when salinity increases. However, removal of Mg^+ is independent on water salinity.

The dry biomass analysis insures that P^{-4} and NO_3^- accumulation in duckweeds' tissue decreases when salinity increases. However, water salinity increase in the range from 0.6 - 2.1 g/l promotes duckweeds accumulation of Na^+, N^{-3}, NH_4^- and Cl^-.

4.3.2.3 Evapotranspiration and evaporation

When the initial duckweeds' biomass was 50 g (intensity = 260 g/m^2) and water salinity was 0.6 g/l, the total volume of water lost by evapotranspiration (ET) over the duckweeds - covered tank was 10450.537 cm^3 and by evaporation (E) over the open - water tank was 12247.462 cm^3, respectively. When the initial duckweeds' biomass was 30 g, the ET and E were 12995.455 and 13751.205 cm^3, respectively (Figure 4.18).

For both tanks of salinity 1.6 g/l, the total ET was 8842.762 cm^3 and E was 11680.012 cm^3 in case of initial duckweeds' biomass was 50 g. When the initial duckweeds' biomass was 30 g, the ET and E were 12048,855 and 13372,905 cm^3, respectively (Figure 4.19).

For both tanks of salinity 2.1 g/l, the total ET was 9221.062 cm^3 and E was 12247.462 cm^3 in case of initial duckweeds' biomass was 50 g. When the initial duckweeds' biomass was 30 g, the ET and E were 12710.88 and 14507.805 cm^3 (Figure 4.20).

The ET was found 0.85, 0.75, and 0.75 times the E for salinity 0.6, 1.6 and 2.1 g/l, respectively, when the initial duckweed biomass was 50 g (intensity = 160 g/m^2). The ET was found 0.94, 0.90, and 0.87 times the E for salinity 0.6, 1.6 and 2.1 g/l, respectively, when the initial duckweed biomass was 30 g.

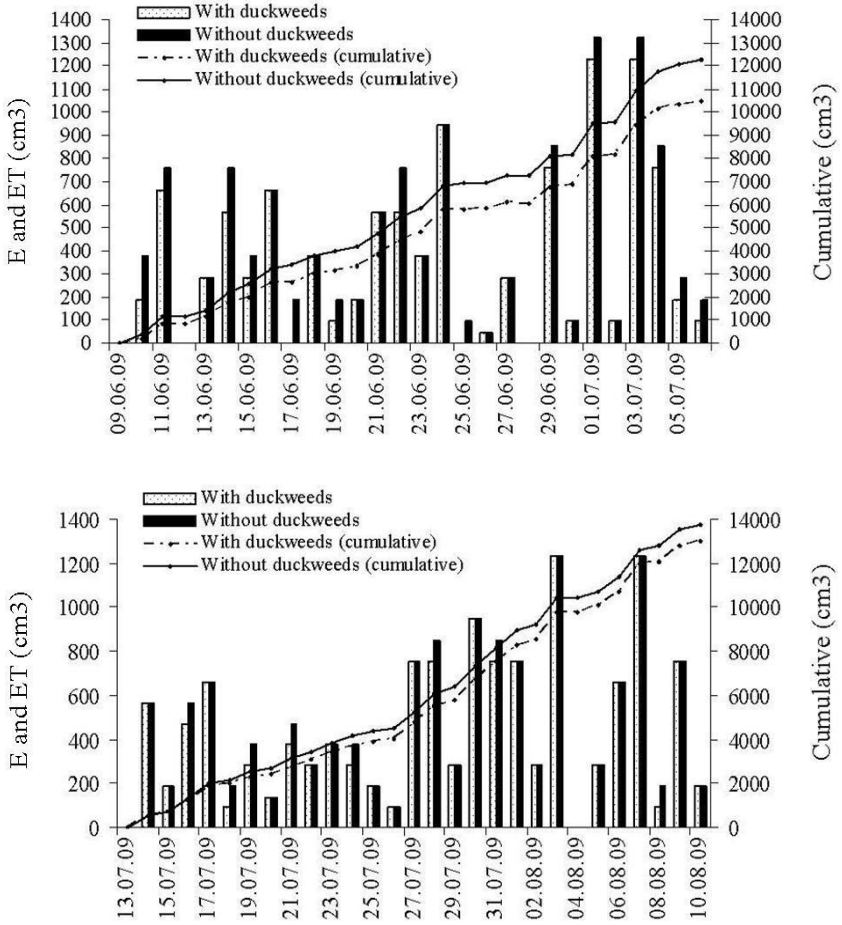

Figure 4.18: Daily and cumulative ET and E for salinity 0.6 g/l when duckweed intensity = 260 g/m^2 (up) and 160 g/m^2 (down)

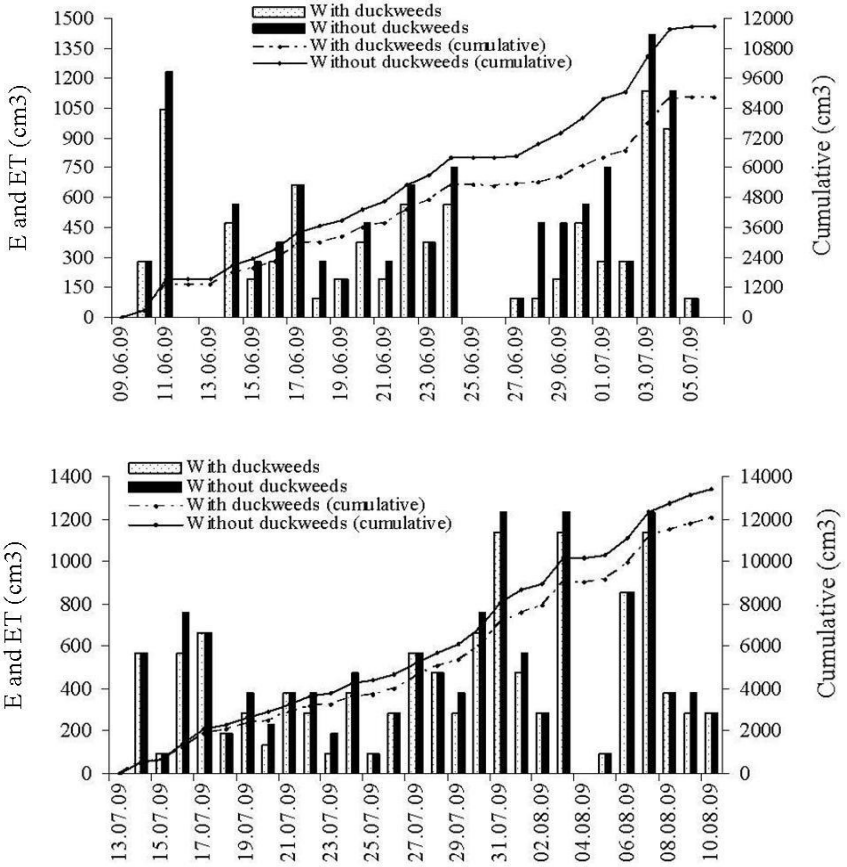

Figure 4.19: Daily and cumulative ET and E for salinity 1.6 g/l when duckweed intensity = 260 g/m^2 (up) and 160 g/m^2 (down)

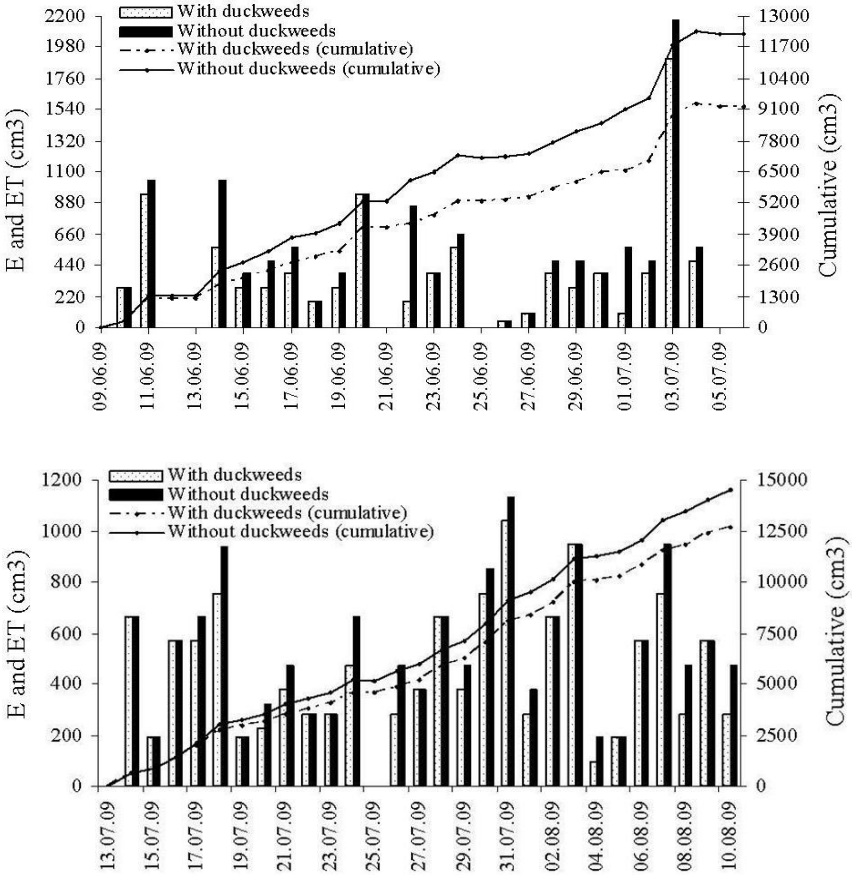

Figure 4.20: Daily and cumulative ET and E for salinity 2.1 g/l when duckweed intensity = 260 g/m^2 (up) and 160 g/m^2 (down)

Thos results prove that duckweeds can reduce the evaporation water losses. According to the ratio between ET water losses in the duckweeds - covered tanks to E water losses in the open - water tanks, duckweed can save up to one quarter of the water volume lost by evaporation. Those results are in agreement

with RAMEY and SCHARDT, (2004); ORON et al., (1987); IQBAL, (1999). RAMEY, (2004) reported that ET water loss by duckweeds is from 0.85 - 0.90 of water loss by evaporation. ORON et al., (1987) reported that ET water loss through a lake that was covered completely by duckweeds decreased by about a third compared to an open-water lake. IQBAL, (1999) insured that duckweeds reduce water loss. Higher duckweeds' biomass (duckweeds' intensity = 260 g/m^2) leads to less evaporation water loss.

4.4 The 2-D numerical simulation of the pond

4.4.1 General and flood case

It is the first time for the general case of the selected pond to be numerically investigated. The dominant parameters in the general case have been taken as follows:

1. Inflow discharge (Q) = 0.003 m^3/s.
2. Friction coefficient of Manning (n) = 0.05 $s/m^{1/3}$.
3. Viscosity (υ) = diffusivity (υ_t) = 0.01 m^2/s.

The maximum water depth (h) = 0.65 m and the water level variations were always very small. Therefore, the water levels were not shown. From Eq. (3.17), the Reynolds number was obtained at different locations in the pond. The flow was laminar in the whole pond in the general case, where the values of Reynolds number ranged from 25 to 1500.

The sensitivity studies concerning dominant parameters have been carried out and compared with the general case.

Firstly, in the flood conditions the inflow discharge was assumed 10 times the discharge of general conditions. Simulations of flood conditions showed that

flood conditions affected both, the hydrodynamics and transport processes of the pond. Flow velocities were higher at flood case than those in the general case (Figure 4.21). The flow was turbulent in many locations as shown in Figure (4.22). The highest values of Reynolds number were found in the area around the inlet with a maximum value = 15000.

From tracer transport simulation, the tracer concentrations [-] at the outlet were plotted for both, the general and flood case (Figure 4.23). These plots showed the residence time distribution curves (RTDs), mean residence times (t_m) and theoretical residence times (t_n) as well as first tracer appearances. The maximum tracer concentration at the outflow was 3.6 [-] after 1.5 hours at flood case but 0.5 [-] after 6 hours at general case. The first tracer appearance was after 0.14 hour for flood case and 2.0 hour for general case. The mean residence time (t_m) was 2.22 hours for flood case (18 % of the general case).

Tracer concentrations distribution via the pond in both, the general and flood case were shown after different time steps (Figure 4.24 and Figure 4.25). After two hours, the maximum tracer concentration was 1.2 [-] and still near to the inlet in the general case, but it was 2.2 [-] and near to the outlet in the flood case. After five hours, the maximum tracer concentration was relatively high in the general case (0.9 [-]) compared to the flood case (0.3 [-]). After ten hours, there was still tracer concentration in the general case which reached to 0.4 [-], but all tracer concentrations almost left the pond in the flood case.

The tracer transport simulations prove that the tracer moves faster and leaves the pond in a shorter period of time in the flood case and that insures the previous results of the hydrodynamic simulations which presented that the flow velocities were higher in flood case.

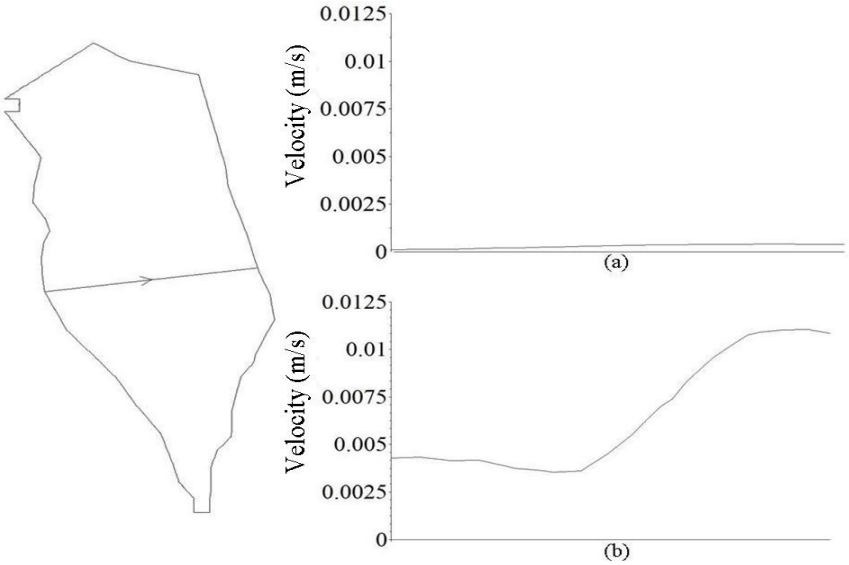

Figure 4.21: Velocity distribution for general case (a) and flood condition (b)

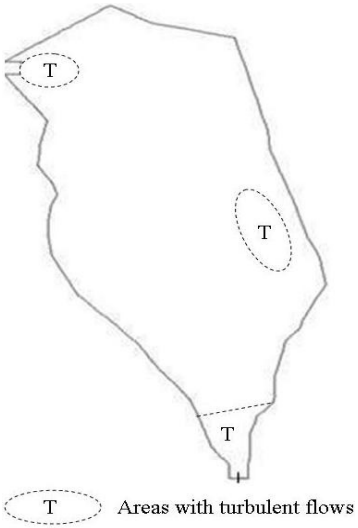

Figure 4.22: Turbulent flows in the flood case

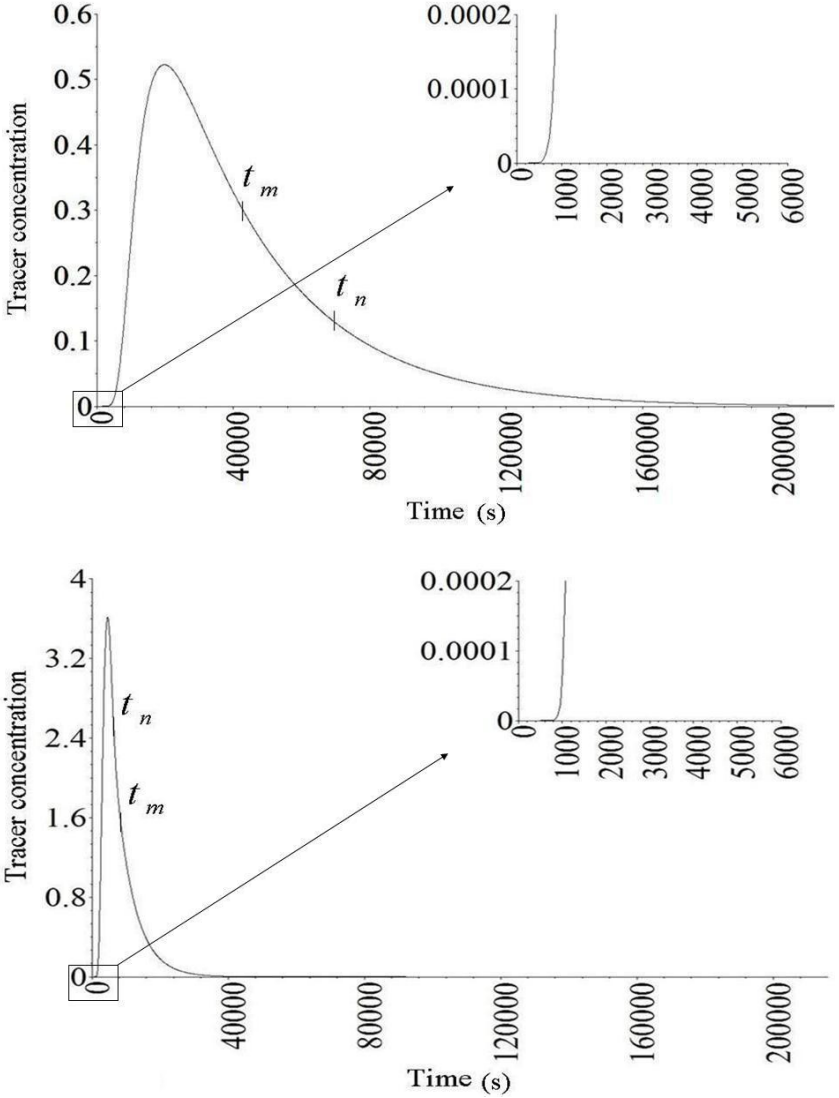

Figure 4.23: RTDs curve, t_m, t_n and first appearance of tracer for general case (up) and flood (down)

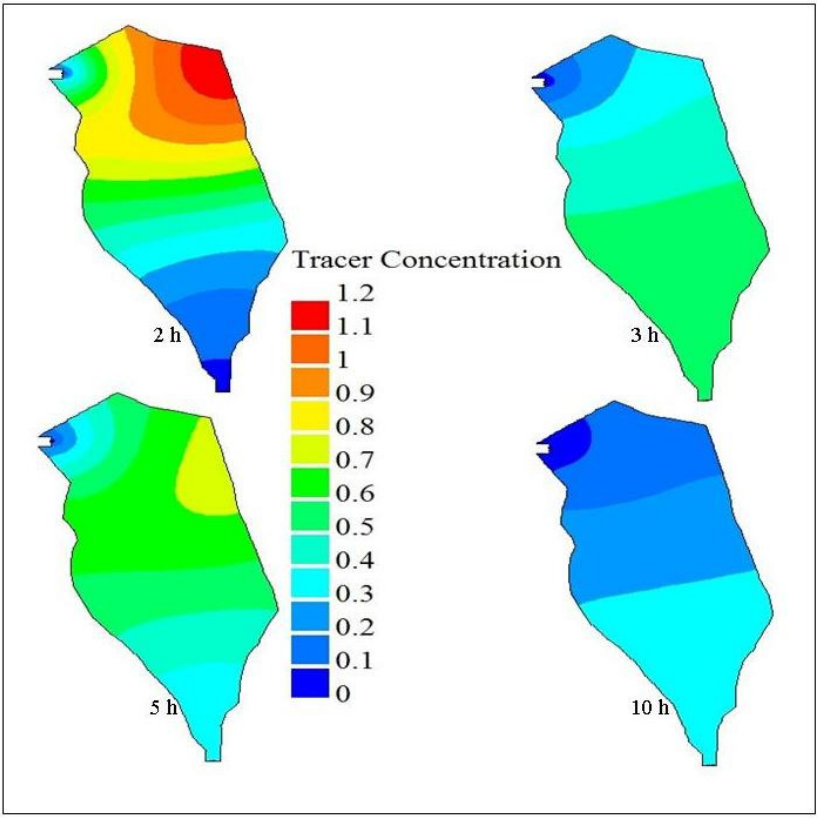

Figure 4.24: Tracer concentrations distribution via the pond after 2, 3, 5 and 10 hours in the general case

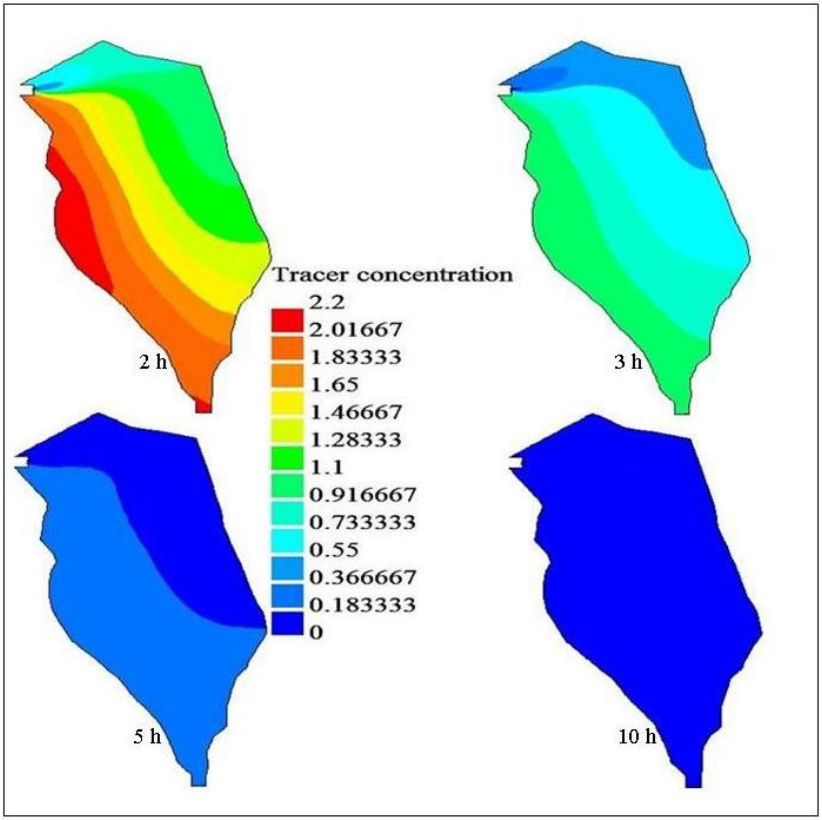

Figure 4.25: Tracer concentration via the pond after 2, 3, 5 and 10 hours in the flood conditions

4.4.2 Bottom friction

Two scenarios for the bottom friction have been carried out with two values of Manning's coefficient (n). The first value was n = 0.05 $s/m^{1/3}$ for a loam soil and normal vegetation distribution including submerged and emergent plants

(MARTIN-VIDE et al., 2008). The second scenario has been undertaken with n = 0.20 s/m$^{1/3}$ representing the expected increase in friction due to many factors such as the big plants, low velocities and wind stress.

Figure (4.26) shows that the pond bottom friction had almost no effect on the hydrodynamics. Flow velocities were almost equal in the pond for both n = 0.20 and 0.05 s/m$^{1/3}$.

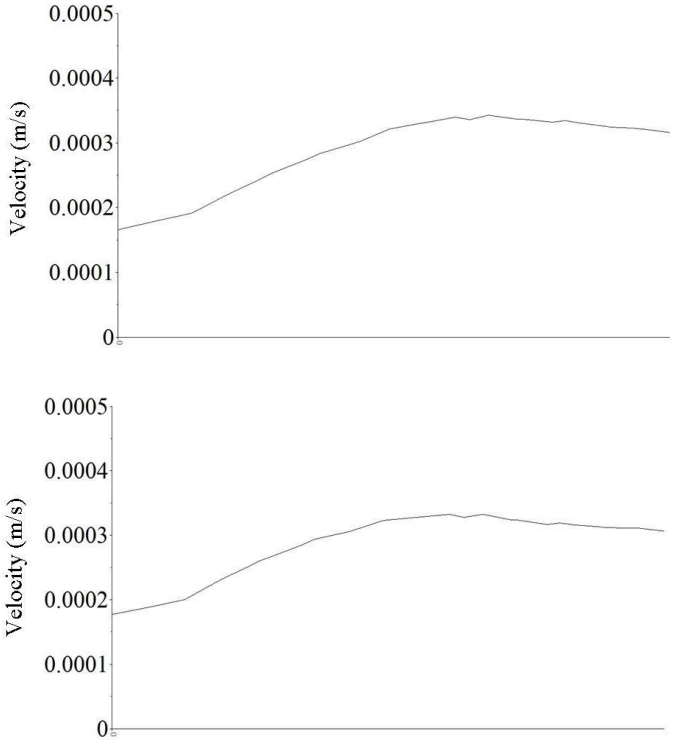

Figure 4.26: Velocity distribution at a cross section in the middle of the pond with Manning's friction coefficient n = 0.200 s/m$^{1/3}$ (up), n = 0.05 s/m$^{1/3}$ (down)

4.4.3 Viscosity and diffusivity

In the general case, the viscosity and diffusivity was $\upsilon = \upsilon_t$ = 0.01 m²/s. The tracer transport simulations were undertaken for the general case as shown previously, and for another two scenarios for viscosity and diffusivity. The scenarios were $\upsilon = \upsilon_t$ = 0.001 m²/s which reflected a low plants' intensity and 0.1 m²/s which reflected a high plants' intensity. The resulting residence times distributions curve (RTDs), t_m, t_n, and first tracer appearance were shown in Figure (4.27). The maximum tracer concentration at the outflow was 0.39 [-] after 8.8 hours at scenario $\upsilon = \upsilon_t$ = 0.001 m²/s but 2.45 [-] after 1.6 hours at scenario $\upsilon = \upsilon_t$ = 0.1 m²/s. The first tracer appearance was after 2.27 hours for $\upsilon = \upsilon_t$ = 0.001 m²/s and 0.07 hour for $\upsilon = \upsilon_t$ = 0.1 m²/s.

The mean residence time (t_m) was very long being 19.8 hours for $\upsilon = \upsilon_t$ = 0.001 m²/s (160 % of the general case). t_m was short for $\upsilon = \upsilon_t$ = 0.1 m²/s being 3.2 hours (25 % of the general case).

Tracer concentrations distributions via the pond with $\upsilon = \upsilon_t$ = 0.001 and 0.1 m²/s were shown after different time steps (Figure 4.28 and Figure 4.29). After two hours, the maximum tracer concentration was 1.7 [-] and near to the middle zone for $\upsilon = \upsilon_t$ = 0.001 m²/s, but it was 1.9 [-] and completely at the outlet for $\upsilon = \upsilon_t$ = 0.1 m²/s. After five hours, the maximum tracer concentration was 0.7 [-] for $\upsilon = \upsilon_t$ = 0.001 m²/s and near to the outlet, but it was 0.4 [-] and completely at the outlet for $\upsilon = \upsilon_t$ = 0.1 m²/s. After ten hours, there was still tracer

concentrations for $\upsilon = \upsilon_t$ = 0.001 m²/s which reached to 0.4 [-], but all tracer concentrations almost left the pond for $\upsilon = \upsilon_t$ = 0.1 m²/s.

The tracer transport simulations for scenarios $\upsilon = \upsilon_t$ = 0.001 and 0.1 m²/s prove that the tracer moves very slowly with $\upsilon = \upsilon_t$ = 0.001 m²/s, and leaves the pond in a short period of time with $\upsilon = \upsilon_t$ = 0.1 m²/s.

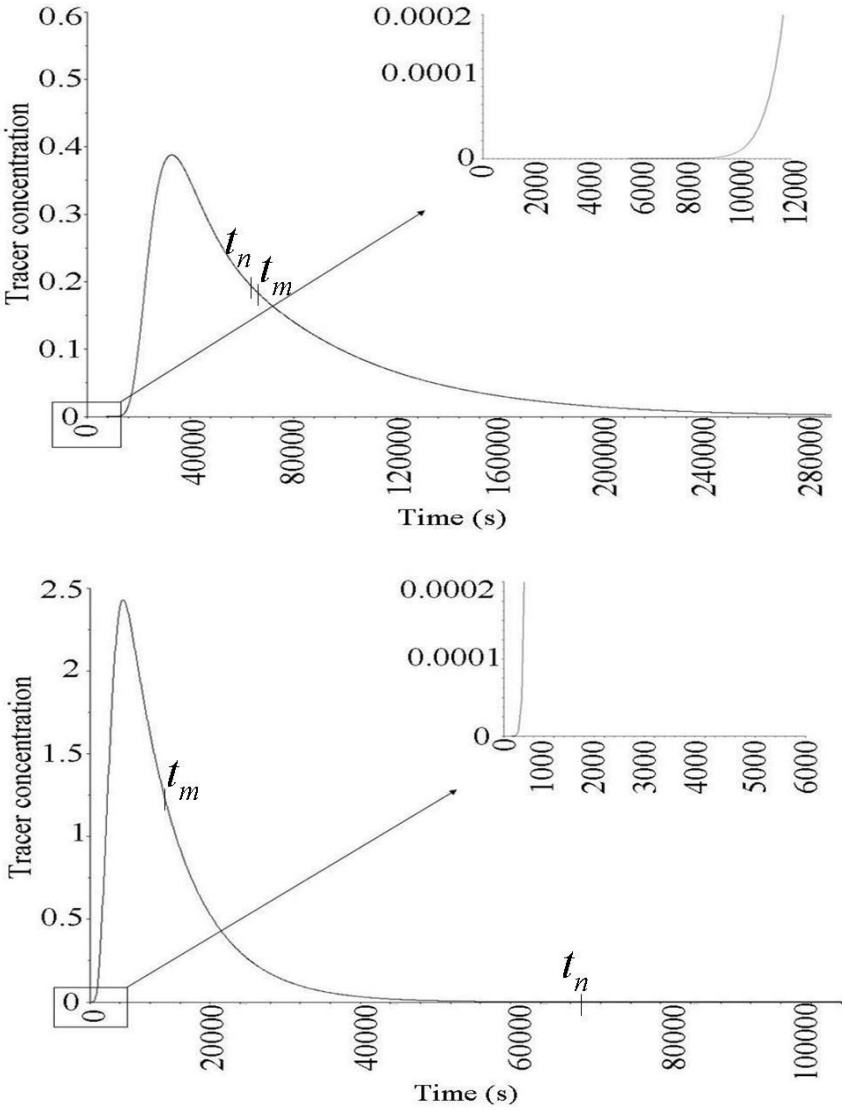

Figure 4.27: RTDs curve, t_m, t_n and first appearance of tracer for $\upsilon = \upsilon_t = 0.001$ (up) and 0.1 m²/s (down)

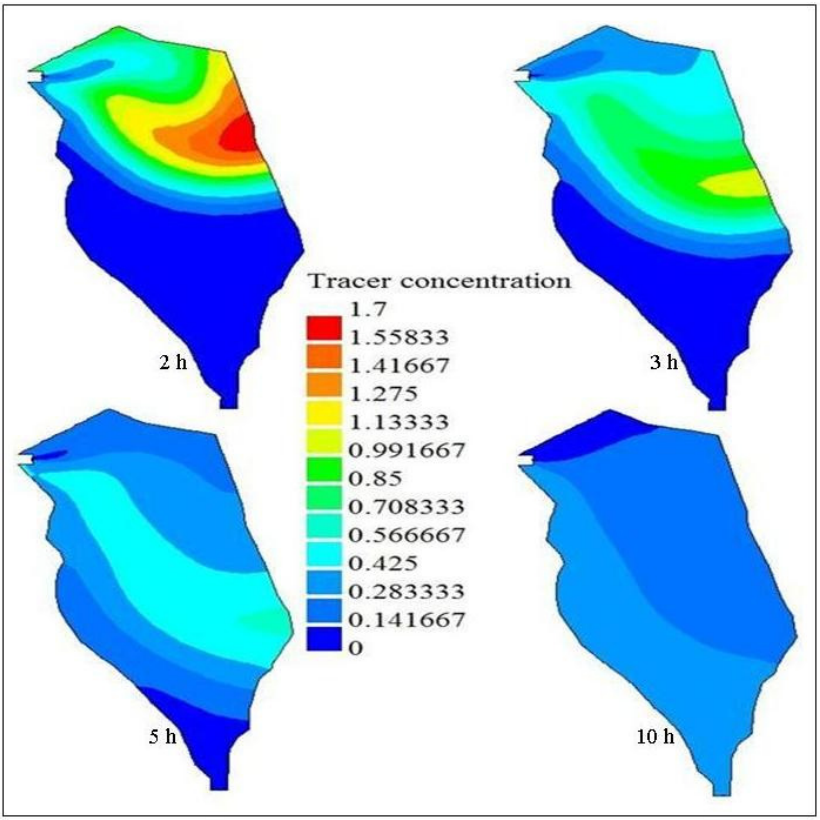

Figure 4.28: Tracer concentrations distribution via the pond after 2, 3, 5 and 10 hours when $\upsilon = \upsilon_t = 0.001$ m²/s

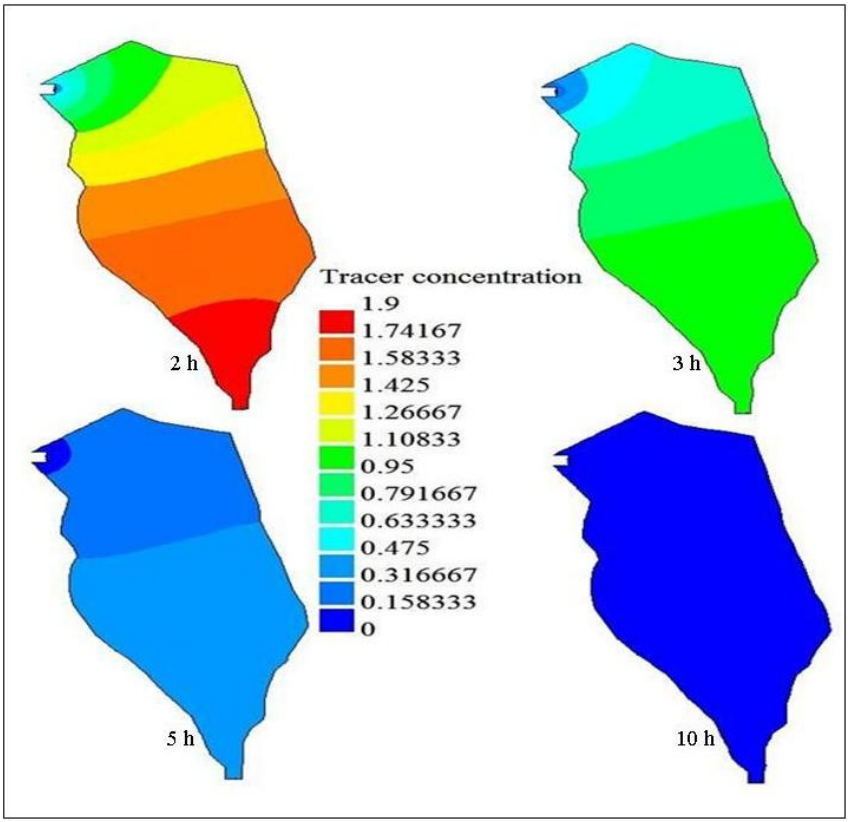

Figure 4.29: Tracer concentrations distribution via the pond after 2, 3, 5 and 10 hours when $\upsilon = \upsilon_t = 0.1$ m²/s

4.4.4 Inflow conditions

In reality, the inlet of the pond depends on the drainage system applied for its agricultural watershed. The inflow can be either via a surface drainage ditch if

the surface drainage system is applied in the agricultural watershed or via a subsurface drainage pipe if the subsurface drainage system is applied.

Two scenarios regarding the inflow design have been undertaken. The inflow was either via a boundary line simulating in reality the surface drainage ditches or a point simulating the subsurface drainage pipes. The inflow distributed more homogenously around the inlet in case of boundary line (Figure 4.30).

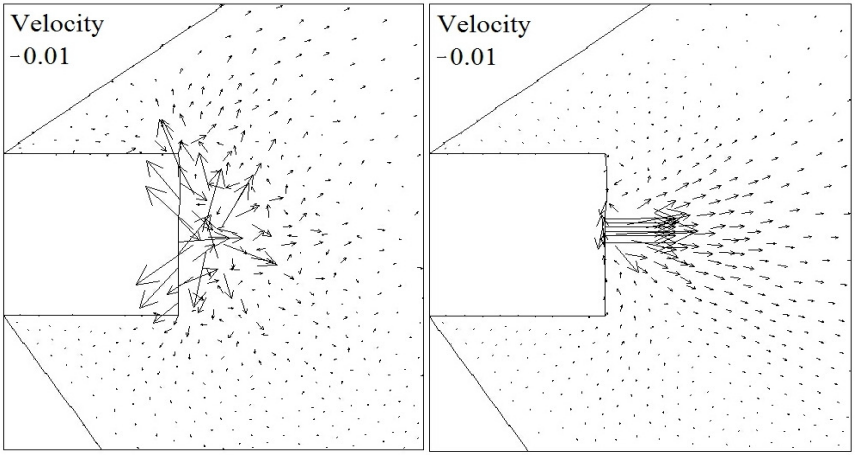

Figure 4.30: The velocity vector (m/s) at the inlet via point (left) and boundary line (right)

4.4.5 Baffles

As expected, the hydrodynamical simulation of the un - baffled pond (general case) showed a bad velocity distribution (Figure 4.31). There were areas with very small velocities which are called dead zones. Another hydraulic problem in the un - baffled pond was the swirling around the inlet which is shown

clearly in Figure (4.33). Therefore, many scenarios of baffles which represented different number, positions and widths of baffles have been undertaken.

From the tested systems, four baffles of 70 % width showed a superior improvement in velocity distribution which reduced the hydraulic problems (Figure 4.32). Baffles in this system lengthened the flow path. No dead zones were found and the flow was more uniform than the un - baffled pond. In addition, the swirling around the inlet almost disappeared (Figure 4.33).

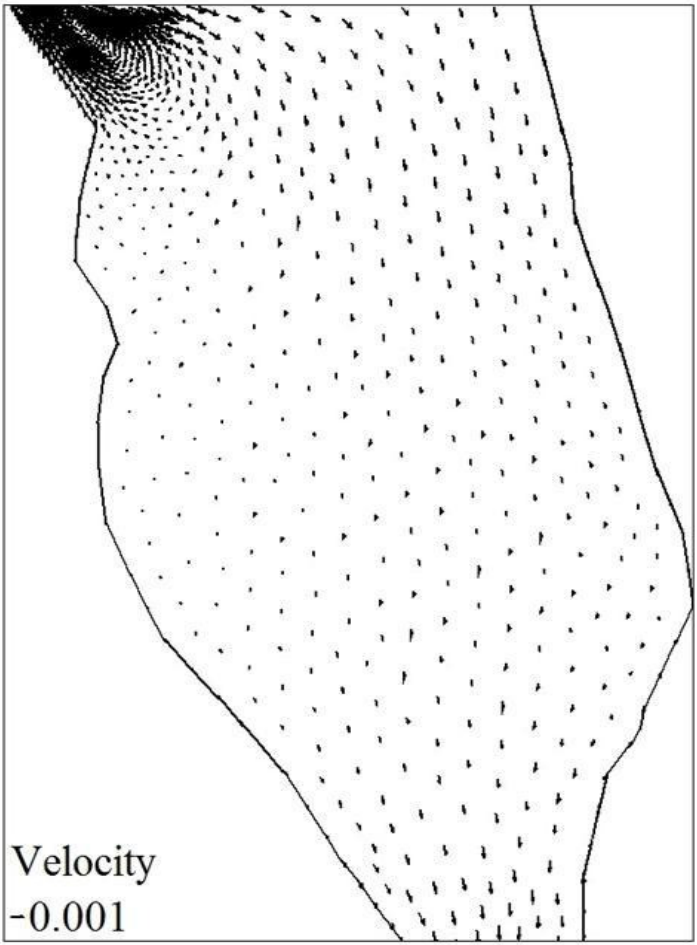

Figure 4.31: Velocity vectors (m/s) in the un - baffled pond

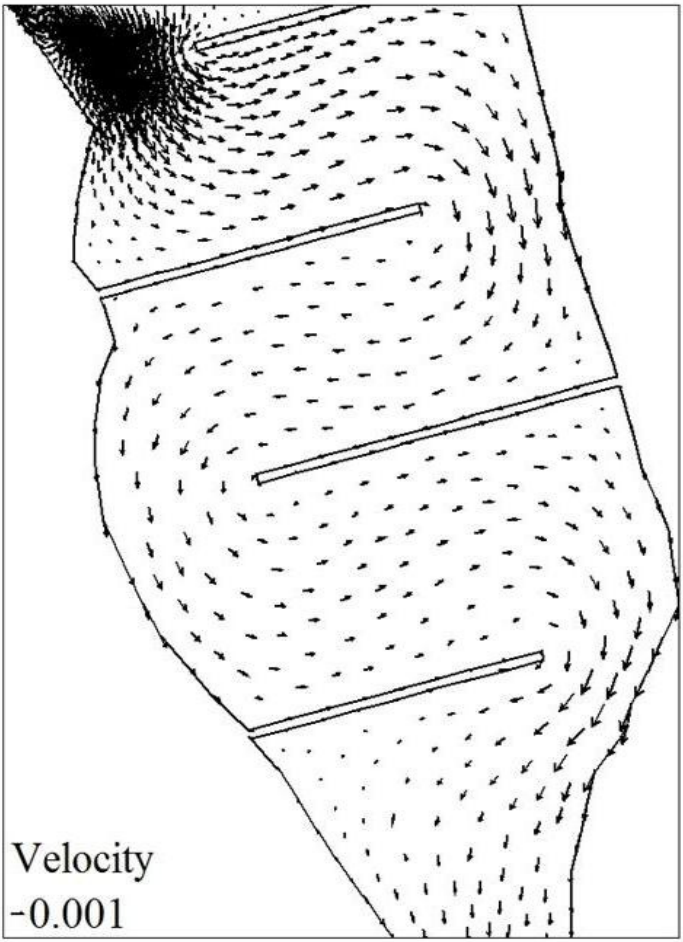

Figure 4.32: Velocity vectors (m/s) in the pond with four baffles of 70 % width

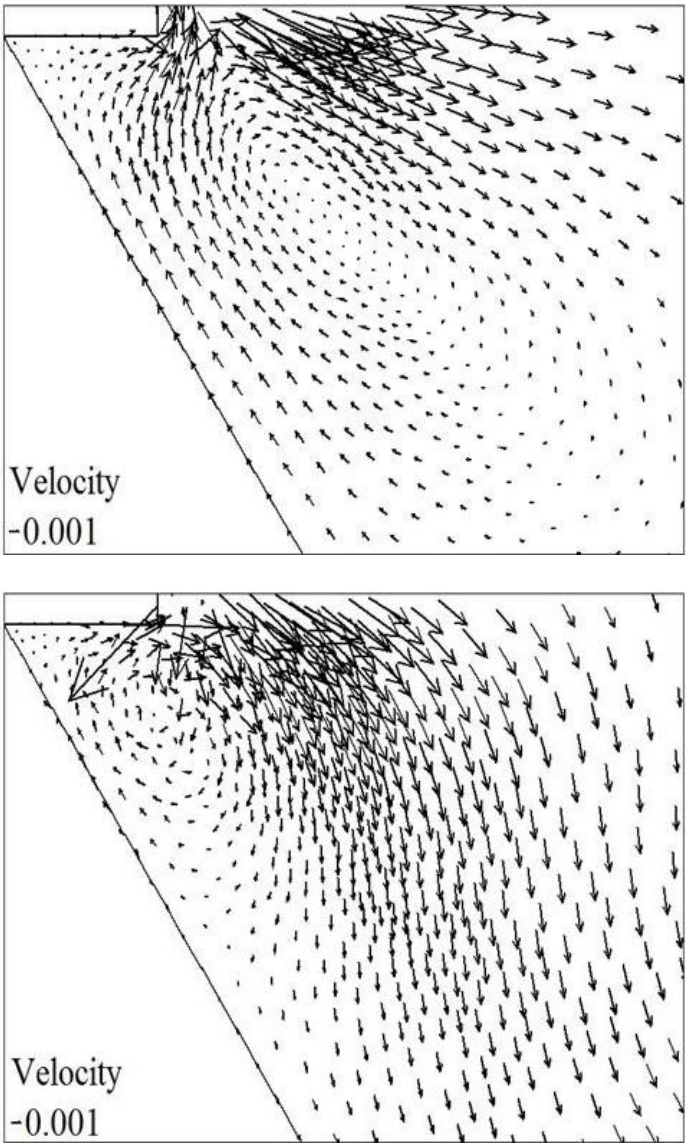

Figure 4.33: The swirling around the inlet in the un - baffled pond (up) and its disappearance in the pond with four baffles of 70 % width (down)

The tracer transport simulations were undertaken for the un - baffled pond and the pond with different number, positions and widths of baffles. Tracer concentrations distributions via the pond for all baffles' scenarios were shown after different time steps (Figure 4.34, Figure 4.35, Figure 4.36 and Figure 4.37).

After two hours, the maximum tracer concentration was found in the same place near to the inlet for all scenarios, but it had different values being 1.2, 1.5, 1.6 and 1.8 [-] for the un - baffled, two baffles of 50 % width, four baffles of 50 % width and four baffles of 70 % width, respectively. This gradual increase in maximum tracer concentration from one scenario to another resulted from slowing the flow via the pond due to different baffles' configurations.

After five hours, the maximum tracer concentration was still near to the inlet with a value of 0.90 [-] in the un - baffled pond. The maximum concentration was distributed regularly along the middle zone of the pond in the scenario of two baffles of 50 % width with a value of 0.62 [-]. For the four baffles of 50 % width and 70 %, the maximum tracer concentration was distributed by the same way, but with higher values (0.66 and 0.75 [-], respectively).

After ten hours, the maximum tracer concentration was 0.4 [-] and near to the outlet in the un - baffled pond. For the two and four baffles of 50 % width, the maximum tracer concentration was 0.50 and 0.53 [-], respectively, and near the outlet. For the four baffles of 70 % width, the maximum tracer concentration was 0.45 [-], but distributed more regularly via the whole pond than the other scenarios.

It is clear from the tracer concentrations distribution that the slowest tracer movement, the most regular distribution and the longest departure - time was observed in the scenario of four baffles of 70 % width.

From Eq. (3.16), (2.4), (2.5) and (3.17), the mean residence time (t_m), theoretical residence time (t_n), hydraulic efficiency (e) and index of short circuiting (I) were obtained, respectively (Figure 4.38 and Table 4.20).

According to Table 4.20, the hydraulic efficiency for all scenarios was higher than the un - baffled pond. Increasing the number of baffles from two to four provided a higher hydraulic efficiency. The maximum hydraulic efficiency was achieved in case of four baffles of 70 % width.

A small increase in the index of short circuiting was observed in case of two baffles. A further small increase was achieved by increasing to four baffles of 50 % width. A large increase was observed in case of four baffles of 70 % width.

The residence time distribution curve insured that the four baffles of 70 % width achieved the best hydraulic efficiency and the most regular flow distribution.

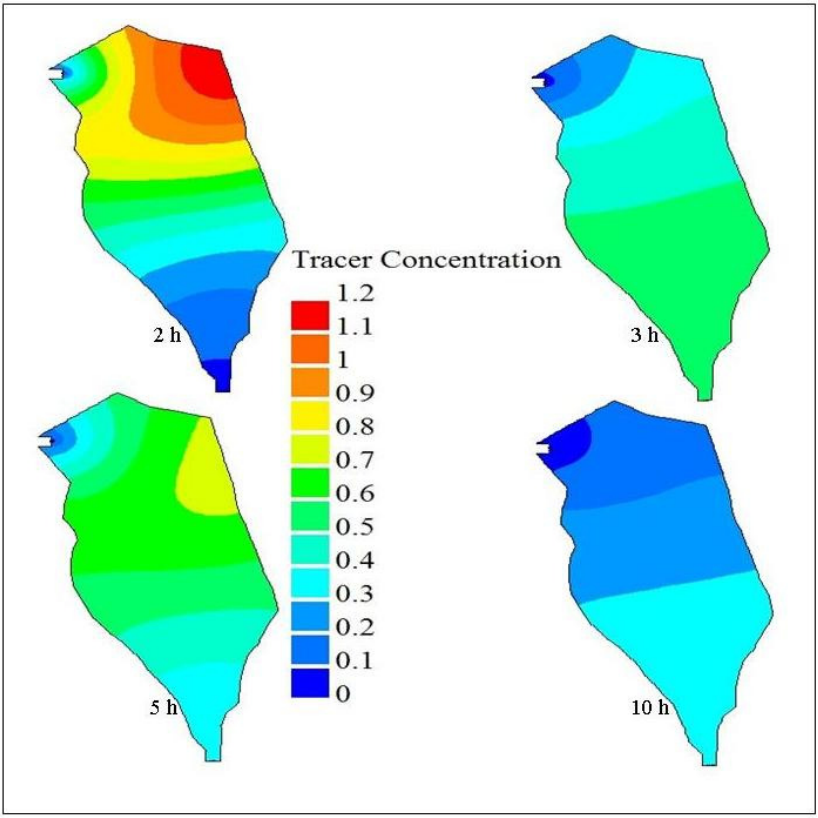

Figure 4.34: Tracer concentrations distribution after 2, 3, 5 and 10 hours via the un - baffled pond

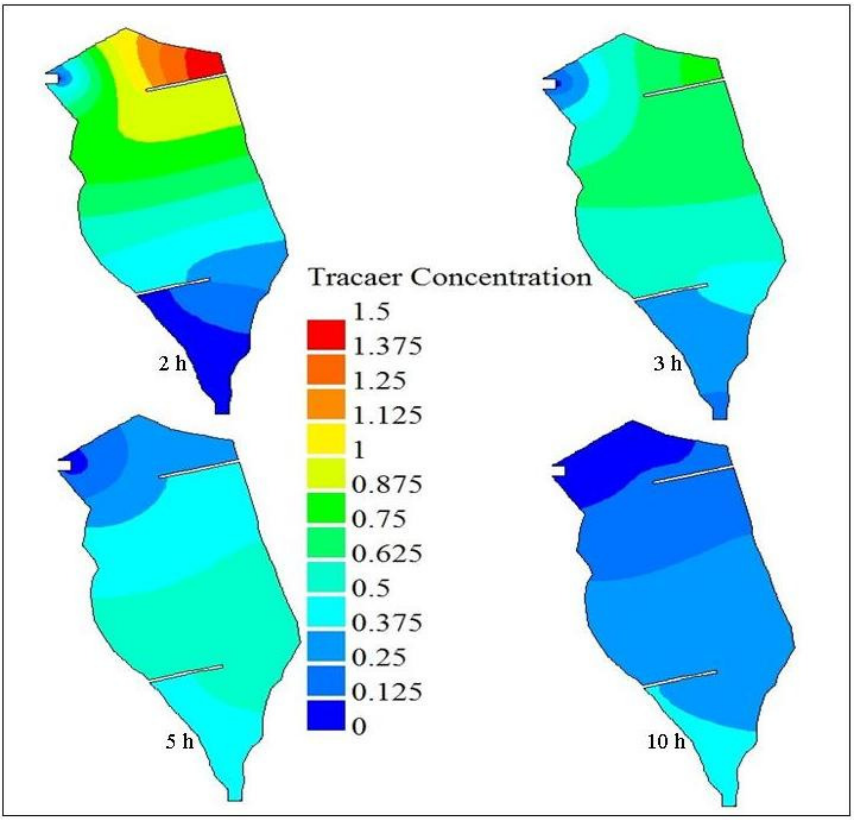

Figure 4.35: Tracer concentrations distribution after 2, 3, 5 and 10 hours via the pond with two baffles of 50 % width

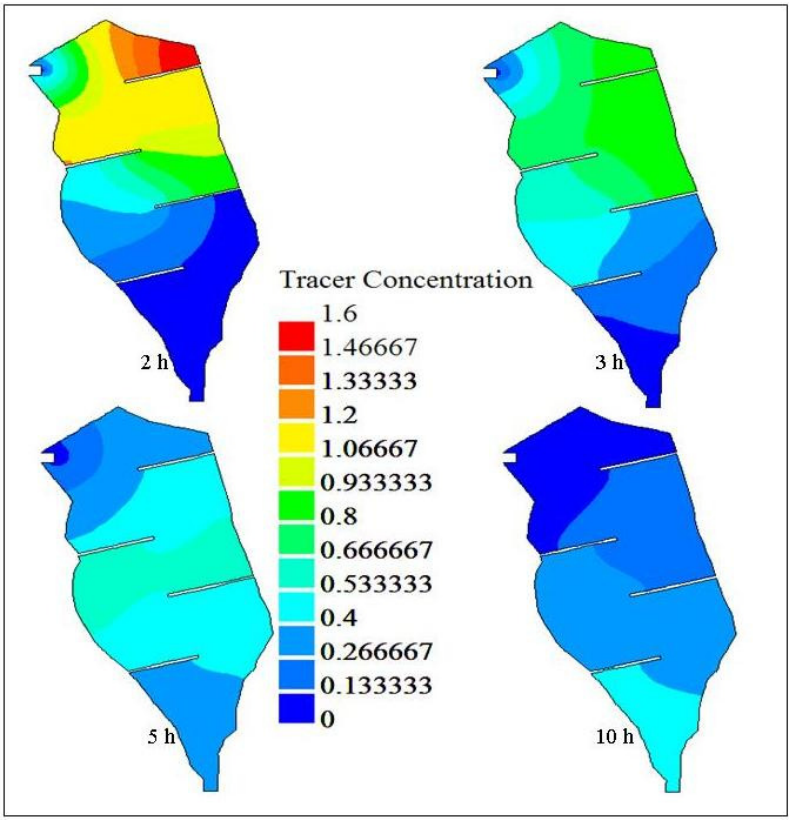

Figure 4.36: Tracer concentrations distribution after 2, 3, 5 and 10 hours via the pond with four baffles of 50 % width

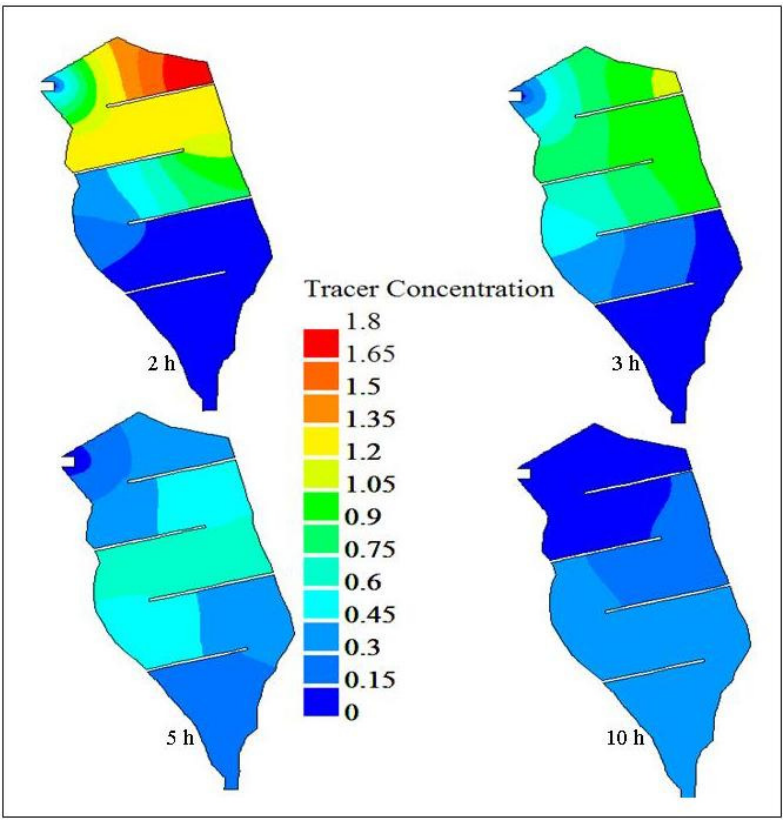

Figure 4.37: Tracer concentrations distribution after 2, 3, 5 and 10 hours via the pond with four baffles of 70 % width

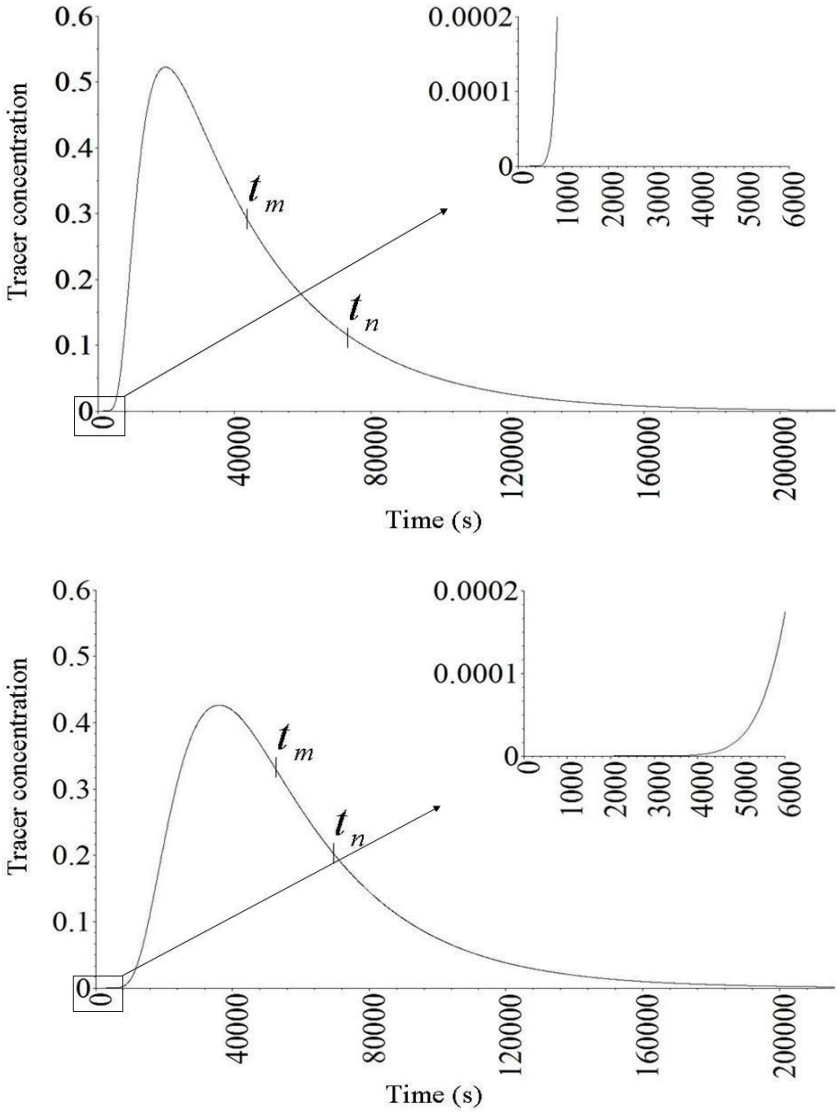

Figure 4.38: RTDs curve, t_m, t_n and first appearance of tracer for the un - baffled pond (up) and pond with four baffles of 70 % width (down)

Table 4.20: The hydraulic parameters for all baffles' scenarios

	t_m (h)	t_n (h)	e (%)	I (h)
Un-baffled	12.14	19.62	61.8	0.05
2-baffles, 50% width	12.90	19.41	66.4	0.057
4-baffles, 50% width	14.27	19.12	74.6	0.07
4-baffles, 70% width	15.59	18.89	82.5	0.10

The mean residence times obtained from the (Table 4.20) were integrated with the first - order salt removal rate to obtain the water salinity at the pond outlet. The results of the outdoor experiments under natural climate conditions in phase (2) showed many values of first order salt - removal rate of duckweeds according to both, the initial duckweeds' biomass and water salinity (Figure 4.16). The value of first order salt - removal which has been chosen here was 12.2 % per day in the case of water salinity 0.6 g/l and duckweeds' intensity 260 g/m^2.

Since the inflow salinity was 650 mg/l, the outflow salinity has been obtained to be 611, 608, 604 and 600 mg/l in the un - baffled pond, the pond with two baffles of 50 % width, four baffles of 50 % width and four baffles of 70 % width, respectively. It is obvious, that the best salt removal efficiency was achieved in the pond with four baffles of 70 % width.

The main results' conclusions of the 2-D hydrodynamic and transport simulations of the selected detention pond are as follows:

- The flood conditions strongly increase the flow velocities in the pond compared to the general case and reduce the mean residence time to 0.18 times.

- The viscosity and diffusivity change the tracer transport behaviour since higher viscosity and diffusivity result in a fast tracer - departure from the pond and a short mean residence time (25 % of the general case). However, lower viscosity and diffusivity result in a slow tracer - departure and a long mean residence time (160 % of the general case).

- Influence of the bottom friction can be ignored since its effect on the pond hydrodynamics is too small.

- The water enters the pond more uniformly via a surface drainage ditch (boundary line) than a subsurface drainage pipe (point).

- Baffles reduce the hydraulic problems in the ponds being dead zones, swirlings and short - circuitings and subsequently improve the whole hydraulic and removal efficiency.

- Ponds' efficiency is dependent on baffles' number, lengths, and positions. The system of four baffles of 70 % width is the most efficient out of the three tested systems with respect to both, hydraulic and removal efficiency.

The results concerning baffles are in qualitative agreement with previous studies. KOSHIAHO, (2002) found that the hydraulic efficiency was highly improved by baffles in two constructed wetland - ponds in agricultural watersheds in southern Finland. WATTERS, (1973) found that baffles of 70 % width gave superior performance compared to 50 % and 90 % baffles widths. SHILTON and HARRISON, (2003) found that the highest efficiency was achieved when four baffles were applied.

5 Conclusions and recommendations

5.1 Conclusions

Investigations concerning duckweeds have been carried out under controlled climate conditions and under natural humid climate conditions with different water salinities and temperatures. In addition, numerical simulations of an actual detention pond in the State of Brandenburg, Germany have been undertaken with the modelling system TELEMAC 2D.

The investigations concerning duckweeds show the following conclusions:

- The optimal growth of duckweeds is achieved at salinities from 0 to 1.6 g/l and temperature 25 ºC.
- Duckweeds can survive up to salinity 3.1 g/l.
- At higher temperatures (35 ºC), duckweeds' growth rates are relatively high.
- At cold temperatures duckweeds do not grow at all but they can keep their healthy conditions.
- Duckweeds accumulate salts in their tissue independent on water salinity and air temperature.

- The salt - uptake rate under natural conditions is first - order reaction kinetics and ranges from 0.5 - 12.2 % per day dependent on both, duckweeds' biomass and water salinity in water temperatures between 15 - 32 ºC.
- Duckweeds accumulate Na^{+}, Cl^{-}, N^{-3}, P^{-4}, NH_4^{-}, and NO_3^{-} in their tissues under different salinity concentrations and temperatures.
- Duckweeds can save up to 25 % of water lost by evaporation.
- Higher duckweeds' intensity is preferable since the duckweeds' intensity of 260 g/m^2 achieves higher salt removal rates and less evaporation water losses compared to 160 g/m^2.

The numerical simulations show the following conclusions:

- Dominant parameters such as flood conditions, viscosity and diffusivity, and inlet design can affect both, the flow and transport processes in detention ponds.
- Flood conditions strongly increase the flow velocities in the pond compared to the general case and subsequently, reduce the mean residence time.
- Higher viscosity and diffusivity result in faster tracer - departure from the pond and shorter mean residence time.
- As inlet, the surface drainage ditch is more preferable than the subsurface drainage pipe, as the water enters the pond more uniformly.
- Influence of the bottom friction can be ignored since its effect on the pond hydrodynamics is too small.
- Design of detention ponds, which is controlled by the geomorphological conditions and composition of the drainage systems, can be modified by baffles that improve both the hydraulic and treatment efficiency.

- The best hydraulic and removal efficiency is achieved in the system of four baffles of 70 % width out of the three tested systems.

In conclusion, the present study proves that the duckweeds - covered ponds can be more applicable, effective and sustainable even in the arid and semi - arid areas, where high salinity of agricultural drainage water, water scarcity and evapotranspiration water loss are found.

5.2 Recommendations

Following the previous results of numerical transport simulations, it is expected to carry out field tracer experiments in the selected pond. The purposes of tracer experiments are:

1. Obtaining the actual mean residence time and the hydraulic efficiency.
2. Calibrating the numerical simulation model used in the present study, specially viscosity and diffusivity.

Design modifications by baffles can be applied in the future in the selected detention pond to improve its performance, since the expected results are good as shown in the present study. General application of baffles in all existing detention ponds can be considered as a tool to improve their performance. However, the numerical simulations for every pond, individually, must be undertaken to choose the best set of baffles configurations.

After the regular harvesting of duckweeds, the harvested biomass can be used to produce ethanol as a source of biofuel - energy. The use of duckweeds as a promising biofuel has not been studied yet. It may play an important part in providing a portion of that liquid fuel which the world needs.

During the hot season in some arid and semi - arid regions, the temperature sometimes exceeds 35 °C that might cause heat stress for the duckweeds if they are cultivated in detention ponds. IQBAL, (1999) recommended many ways for

relief of heat stress during extremely hot days being: manual dunking of the plants, splashing or spraying them with a fine mist of water and cultivation of plants on the embankments of the ponds that can shade the duckweed cover and protect it from direct sunlight. These ways are efficient and immediate ways for lowering temperatures by 5 °C to 10 °C.

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Annexes

Annex A: Standards for evaluation of irrigation water

Guidelines to evaluate irrigation water quality problems [APHA 1980].

Water Parameter	Symbol	Unit	Usual range in irrigation water	
1. SALINITY				
Electrical Conductivity	EC_w	dS/m	0 - 3	dS/m
Total Dissolved Solids	TDS	mg/l	0 - 2000	mg/l
2. CATIONS AND ANIONS				
Calcium	Ca^{+2}	me/l	0 - 20	me/l
Magnesium	Mg^{+2}	me/l	0 - 5	me/l
Sodium	Na^{+}	me/l	0 - 40	me/l
Chloride	Cl^{-}	me/l	0 - 30	me/l
Sulphate	SO_4^{-2}	me/l	0 - 20	me/l
3. NUTRIENTS				
Nitrate-Nitrogen	NO_3^{-}	mg/l	0 - 10	mg/l
Ammonium-Nitrogen	NH_4^{-}	mg/l	0 - 5	mg/l
Phosphate-Phosphorus	PO_4^{-3}	mg/l	0 - 2	mg/l
Potassium	K^{+}	mg/l	0 - 2	mg/l

Annex B: Standards for mixing drainage water with canal water (reuse)

Standards for mixing (Article 65 of ministerial decree 8/1983 on Law 48/1982), Ministry of Water Resources and Irrigation, Egypt [NWRP 2005].

Parameter name	Abbreviation	Standard (mg/l)
Acid balance	pH	7 - 8.5
Alkalinity total		50 - 200
Ammonia	NH_4^-	0.5
Arsenic	As^{+2}	0.05
Biological Oxygen Demand	BOD	10
Cadmium	Cd^{+2}	0.01
Chemical Oxygen Demand (Dichromate)	COD	15
Chemical Oxygen Demand (Permanganate)	COD	6.0
Coliform bacteria (total)		5000 MPN/100 ml
Colour		100 units
Copper	Cu^{+2}	1.0
Cyanide		0.1
Fluoride	F^-	0.5
Iron	Fe^{+2}	1.0
Mercury	Hg^{+2}	0.001
Nitrate	NO_3^-	10
Oxygen dissolved	DO	5.0 (minimum)
Phenol		0.02
Phosphate	PO_4^-	1.0
Smell		2 degree when cold
Temperature		5 ^oC above normal
Total Dissolved Solid	TDS	500
Zinc	Zn^{+2}	1.0