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Topic 4: Application of Alternative Drainage Methods

SOIL SALINITY CONTROL UNDER BARLEY CULTIVATION USING A LABORATORY DRY DRAINAGE MODEL

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Abstract

The drainage of agricultural fields is carried out in order to control soil salinity and the water table. Conventional drainage methods such as lateral drainage and interceptor drains have been used for many years. These methods increase agriculture production; but they are expensive and often cause environmental contaminations. One of the inexpensive and more environmental friendly methods that can be used in arid and semi-arid regions to remove excess salts from irrigated lands to non-irrigated or fallow lands is dry drainage. In the dry drainage method, natural soil system and the evaporation of fallow land is used to control soil salinity and the water table of irrigated land. There are few studies about dry drainage concepts. it is also important to study soil salt changes over time because of salt movements from irrigated areas to non-irrigated areas especially under plant cultivation. In this study a laboratory model which is able to simulate dry drainage was used to investigate soil salts transport under barley cultivation. The model was studied during the barley growing season and for a constant water table. During the growing season soil salinities of irrigated and non-irrigated areas were measured at different time. The Results showed that dry drainage can control the soil salinity of an irrigated area. The excess salts leached from an irrigated area and accumulated in the non-irrigated area and the leaching rate changed over time. Soil surface salinities of non-irrigated areas increased with time. At the end of the experiment, the increase of the mean soil salinity of the non-irrigated area was 2.81 times more than the increase of the mean soil salinity of the irrigated area. In arid and semi-arid regions where suitable conditions exist, dry drainage can be used as a useful management tool to control soil salinity.

KEY WORDS: Barley, Dry drainage, Salt movement, Shallow ground water.

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Introduction

During the last 3-4 decades, as the demand for agricultural productions increased the irrigated lands also increased up to 300%. This has imposed a further increase in soil salinization and a relative decrease in crop yield (Poustini and Siosemardeh, 2004). In arid and semi-arid regions, farmers often use saline water to irrigate their fields because of shortage of good quality water resources. This causes soil and water contaminations and reduces agricultural productions. Drainage is a common method to reduce salt accumulation in soil especially when irrigating with saline water. Salt leaching is one of the most important aims of the drainage systems, but it causes fertilities and pesticides to be removed from soil profile and pollute surface water and ground water resources (Deng, 1998). In recent years, researchers have tried to find more suitable and environmental acceptable method for drainage of agricultural fields. For example subsurface irrigation and controlled drainage are irrigation methods which can reduce pollution and still provide sufficient irrigation requirement (Ragab, 2002; Skaggs, 1999). Results of different researches have shown that it is beneficial if crop rotation is considered for land reclamation programs to decrease soil salinity. The subsurface drainage systems in agricultural fields are expensive and cause environmental pollutions. Dry drainage is a new concept for drainage of agricultural fields which has less environmental impacts and with low cost as compared to subsurface drainage systems can reduce soil salts and leach excess salts (Konukcu and et al., 2006). Greenwood et al. (1994) first have introduced dry drainage. In this method part of the field is considered as irrigated area and another part is considered as non-irrigated area or fallow land. Drainage occurred through soil of irrigated area and salts will leach to the non-irrigated area or fallow land. The gradients from irrigated area to non-irrigated area cause salts and excess water movements (Khouri, 1998). Dry drainage is efficient and applicable for conditions of high water table, high capillary rise and high potential of evaporation. These conditions are visible in many arid and semi-arid regions that suffer from salinity problems (Khouri, 1998). Konukcu, et al. (2006) reported that dry drainage is a sustainable solution to water logging and salinity problems in irrigated area. There are few researches about dry drainage and its practical use (JingWei and et al., 2009; Khouri, 1998). Previous studies had confirmed that dry drainage is more economical and environmental acceptable drainage method for agricultural fields. Therefore, the objective of this study was to simulate soil salinity under dry drainage with barley cultivation using a laboratory model.

Materials and methods

In this study a laboratory dry drainage simulation model was used to investigate soil salinity control under barley cultivation at Isfahan University of Technology, Isfahan, Iran. The model was made from galvanized sheet with thickness of 4 mm and with dimensions of 2 m length, 0.5 m width and 1 m height as shown in Fig.1.

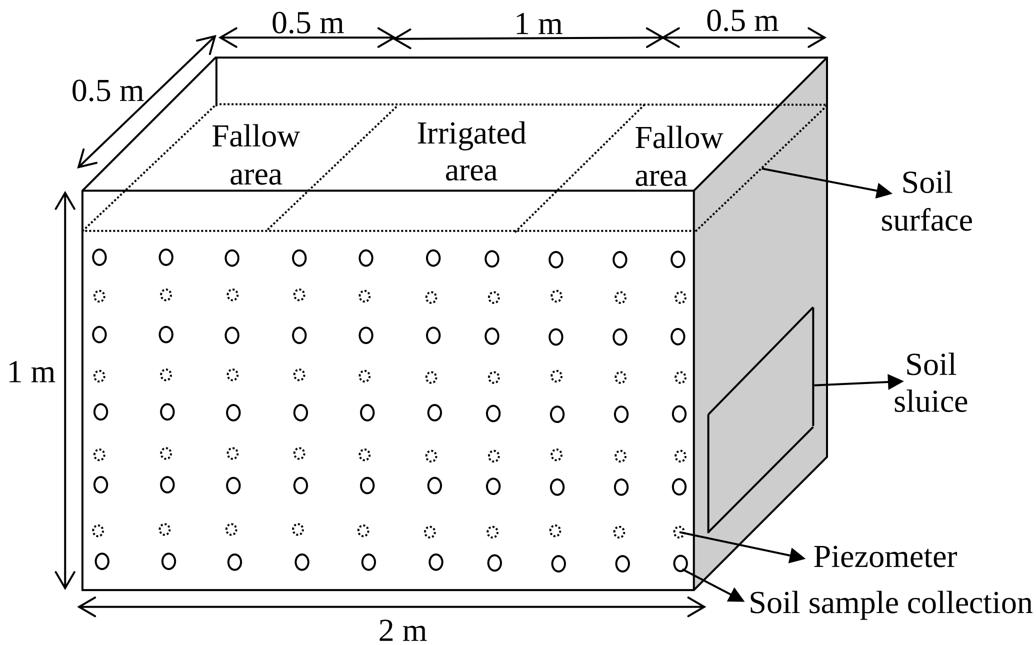

Figure 1. The schematic of the laboratory dry drainage simulation model

To observe water flow and ground water level in the model, one side of the model was made of the Plexiglas with thickness of 8 mm. Another side of the model had a grid system with vertical distance of 0.2 m and horizontal distance of 0.1 m. Half of these grid points were connected to polyethylene piezometers with inside diameter of 5 mm to measure and monitor groundwater level and other half were used to collect soil samples for soil moisture and soil salinity measurements. To drain water and to obtain desire water table, a drainage valve was installed at the bottom of the model. To obtain uniform water table, sand filter was placed at the bottom of the model. A water level controller connected to the drainage valve at the bottom of the model. It was able to raise water from the bottom to the top smoothly until it reaches the desire water level which was 0.6 m from the soil surface. The soil used for the study was loamy which was taken from an agricultural field. The physical and chemical characteristics of the soil are given in Table 1. The model was filled layer by layer by the soil and each layer was compacted uniformly to reach the bulk density which is close to bulk density of actual field. Model was divided into two equal sections of irrigated and non-irrigated (fallow) areas in such a way that due to hydraulic gradient changes, soil water and salt movements occur naturally between these two sections. The irrigated area was cultivated by barley and was irrigated with irrigation water which its characteristics are shown in Table 2. Irrigation water salinity was obtained by mixing good quality irrigation water with the saline water. The maximum irrigation interval was 3 days and irrigation amount changed with time. With irrigation, soil moisture was raised to field capacity and water table was raised to 0.6 m depth below soil surface. The experiment was carried out for one complete growth season of the barley and mass soil water and salinity of irrigated area and non-irrigated area were measured at five different times of 0, 21, 42, 63 and 84 days after planting using soil samples taken at different locations of the model.

Table 1. The characteristics of soil

Characteristics	Sand	Silt (%)	Clay	Bulk density (gr/m^3)	EC (dS/m)	pH
value	52	28	20	1.6	3	8

Table 2. The characteristics of irrigation water

Characteristics	Na^+ (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	K^+ (meq/L)	EC (dS/m)	pH
value	5.99	9.15	8.14	2.94	3	7.5

Results and discussion

Fig. 2 shows soil surface moistures of irrigated and non-irrigated areas for 0, 21, 42, 63 and 84 days after planting. Soil moistures of irrigated area and non-irrigated areas were equal at the beginning of the experiment. After plant cultivation, for first few weeks the difference between soil surface moistures increased due to irrigations. The differences decreased because of water movements from irrigated area to the non-irrigated area. Water movements occurred due to hydraulic gradient between two areas. Irrigations of irrigated area and also evaporation of soil surface of non-irrigated area increased the hydraulic gradient and caused water movements from irrigated area to non-irrigated area.

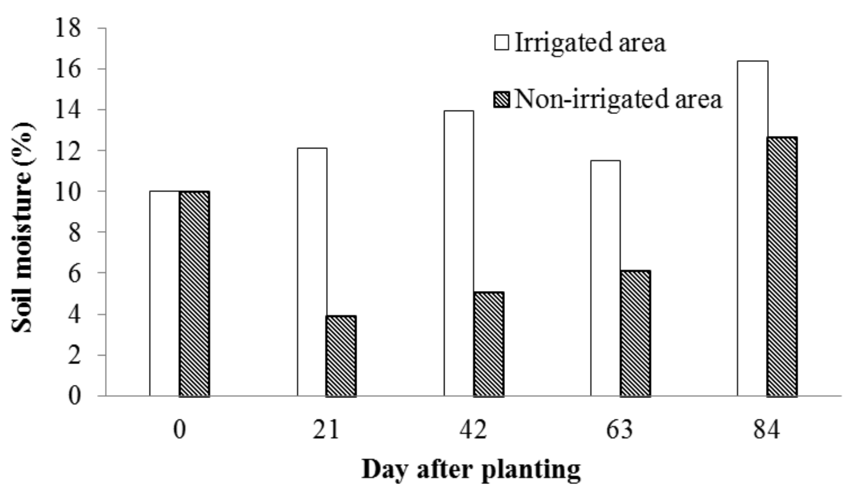

Figure 2. Soil surface moistures for different times after planting

Fig. 3 shows soil moistures at different depths for 84 days after planting for irrigated and non-irrigated areas. Soil moistures in both areas increased by soil depth due to capillary rise from water table. Soil moisture at each depth for the irrigated area was more than the non-irrigated area. The difference of soil moisture at each depth of irrigated and non-irrigated areas increased as soil depth decreased due to irrigation of irrigated area and evaporation of non-irrigated area.

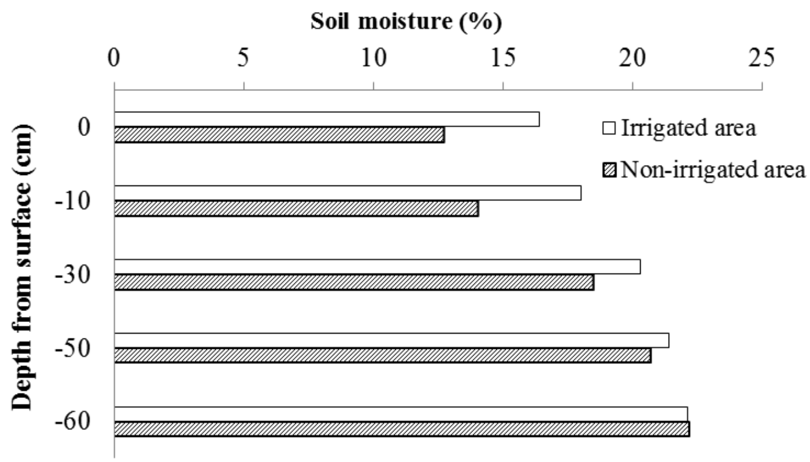

Figure 3. Soil moistures at different depths for 84 days after planting

Soil surface salinities for 0, 21, 42, 63 and 84 days after planting during the growing season are shown in Fig. 4. Soil surface salinities of both irrigated and non-irrigated areas increased with time. Soil surface salinities of non-irrigated area increased more than the irrigated area. Increase of soil surface salinities of irrigated area and non-irrigated area were 45 and 170 percent respectively. Irrigation by saline water caused salt accumulates in irrigated area. The considerable amount of these salts leached from irrigated area to the non-irrigated area because soil water movements from irrigated area to the non-irrigated area due to evaporation of non-irrigated.

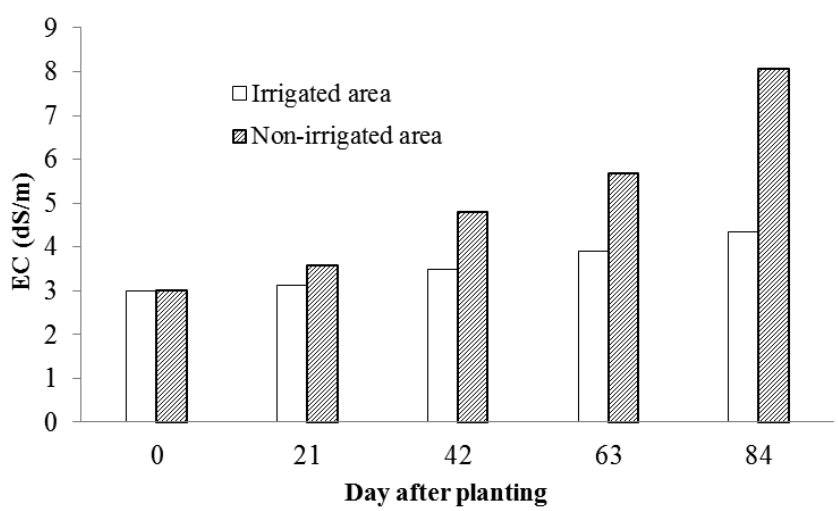

Figure 4. Soil surface salinities for different times after planting

Soil salinities at different depths for 21 and 84 days after planting are shown in Fig. 5. Soil salinity of the non-irrigated area was more than the irrigated area. Soil salinities decreased as the soil depth increased due to water and salt movements. Water movements and consequently salt movements occurred from irrigated area to the non-irrigated area due to hydraulic gradients.

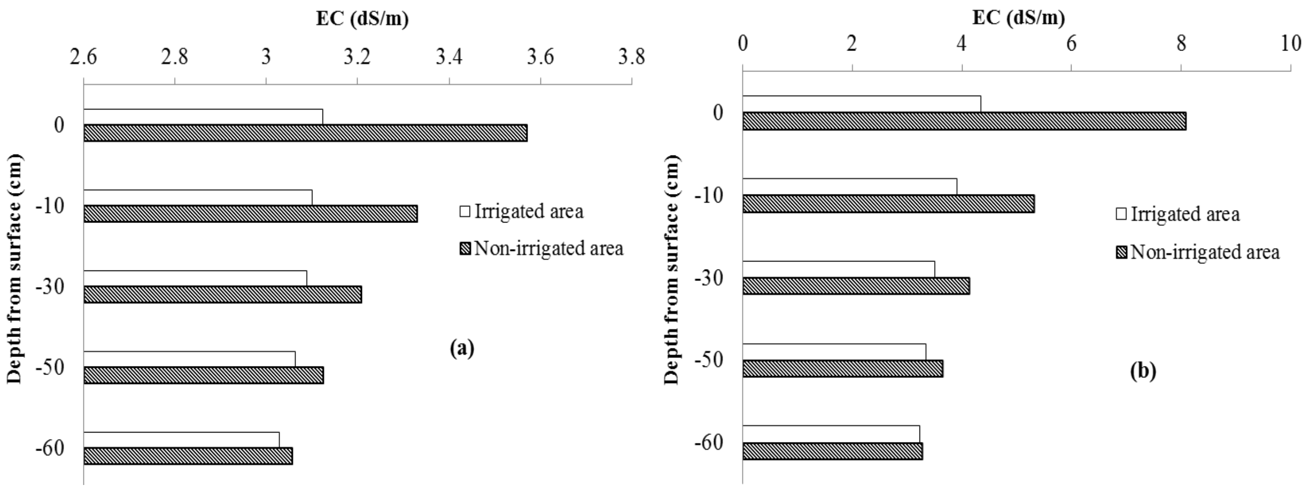

Figure 5. Soil salinities at different soil depths, a) for 21 days after planting and b) for 84 days after planting

Conclusion

Dry drainage is a new method that can be used in arid and semi-arid regions to remove excess salts from irrigated lands to the non-irrigated or fallow lands. In this method, natural soil system and evaporation of fallow lands are used to control soil salinity. Dry drainage is more applicable for conditions of high water table, high capillary rise and high potential of evaporation. In this study, soil salinity under dry drainage with barley cultivation was simulated using a laboratory model. The hydraulic gradient between irrigated area and non-irrigated area caused excess water and salt movements from irrigated area to non-irrigated area. The concept of dry drainage can provide better conditions for plant growth by reducing excess salts from irrigated area. Further studies of dry drainage under different conditions of soil types, water table depths, salinities and crops are recommended.

Acknowledgement

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IN-STREAM WETLAND AS A POTENTIAL LOW COST TREATMENT TECHNOLOGY IN RURAL AREAS

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Abstract

The countries of the Middle East and North Africa region have 5% of the world's population but have less than 1% of the world's renewable fresh water. The region is one of the driest in the world and poorly endowed with natural freshwater supplies. The annual per-capita water availability in 1960 was about 1550 m3 and has fallen by 40% to about 650 m3 today and it is expected to be about 450 m^3 in 2025.

Wastewater treatment in Egypt's rural areas as well as in many other countries lags far behind potable water supply. Only urban centers and some larger rural villages possess wastewater treatment facilities. Economics of scale makes conventional wastewater treatment cost prohibitive in smaller more dispersed rural settlements. Domestic wastewater is typically discharged directly or indirectly to drainage canals. This practice has contributed to widespread degradation of drainage water quality, thus negatively affecting the reuse of drainage water plans in Egypt. Several treatment alternatives that vary in efficiency and costs are available. The natural wastewater treatment requires relatively low capital investment when flat land is available at reasonable price. Among the natural treatment systems, in-stream wetland has a high potential for application in rural areas of Egypt where the treatment process takes place within the drain. Thus, it needs much less land, which is easily maintained, and which can absorb shock loads with relatively less capital and operational costs. All these features have made in-stream wetland a very attractive option for rural communities. Pilot studies in the Nile Delta drain system were conducted to demonstrate the technical feasibility of the in-stream study and adopt the design criteria suited for the Egyptian environment. One pilot area was selected among several potential sites in the Nile Delta using multi-criteria analysis. Baseline studies have been conducted to collect the data/information required for the design of in-stream wetlands. The studies included an intensive water quality monitoring program, hydraulic characteristics, physical survey, socioeconomic survey, developing public awareness program and others related activities.

The HEC-RAS modeling system is used for the calculation of water surface profiles for steady gradually varied flows of the selected drain. MATLAB software is used to develop an external transport module to simulate the convection, advection, diffusion and decay of different pollutants. A group of 25 numerical runs in a matrix were simulated to test the impact of physical interventions on drain surface water profile, detention time and pollutants removal efficiency. The baselines

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studies show that the self-purification capacity of the selected drain without any physical engineering intervention varies within a narrow range from 29% to 37% for BOD removal with the treatment of detention time from 6 to 8 hours. The proposed system could have a detention time up to 68 hours using limited physical intervention such as sedimentation traps, weirs and baffles. Simulation of different design alternatives indicate that the removal efficiency of such a system can reduce 60% of BOD and 70% of TSS. Introducing aquatic plants would improve the removal efficiency especially for nutrients and pathogens. The performance of the in-steam wetland treatment system under similar conditions in Egypt is expected to be equivalent to the advanced primary to secondary conventional treatment.

KEY WORDS: Drainage water reuse, Natural treatment system, Water quality modeling.

Introduction

The emphasis on increased reuse of drainage water for irrigation is essential as Egypt expands its agricultural land base to meet the food supply requirements of a rapidly growing population. The sanitation facilities of Egyptian rural areas far behind potable water supply. This situation has contributed to widespread degradation of drainage water quality and so, the reuse of drainage water plans in Egypt. A major concern when considering drainage water reuse is whether the drainage water quality is within the allowable limits for different uses as outlined by the water quality standards. Thus, more attention needs to be directed to improve drainage water quality [El Sayed A., 2009]. Introduction of in-stream wetland treatment system on existing drains is an effective, cheap, and simple treatment alternative to improve drainage water quality. More studies on using this approach on the tertiary drain level are required. The current research study aims at verifying the design criteria and demonstrating the effectiveness of the in-stream wetland treatment system under Egyptian or similar conditions. Implementation of such experiment involves selection of the pilot area site, conducting baseline studies, design and construction of the wetland treatment scheme and carrying out environmental management plan for the scheme operation. The objective of this paper is to present the site selection process, major finding concluded form the baseline & design studies and potential of having a successful in-stream wetland treatment scheme.

In-stream Wetland Treatment System

Main Elements of In-Stream Wetland

Wetland system can reduce high levels of BOD, suspended solids and nitrogen as well as significant levels of metals; trace organic and pathogens [Reed et al., 1988]. The removal of settable organic is very rapid in all wetland systems due to the quiescent conditions in the free water surface types and the deposition and filtration in the vegetated submerged bed systems. Similar results have been observed as the over flow of systems where close to 50% of the applied

BOD removed in the upstream reach. Figure (1) illustrates a typical in-stream wetland treatment system which consists of the following elements [Harza, 2000]:

- Sedimentation zone to reduce suspended matter load;
- Two aquatic plant zones to enhance biological treatment process;
- Number of submerged berms to manage the required detention time for treatment;
- Floating vegetation barriers (two to three) to avoid weed and vegetation spreading;
- Control weir to manage drainage water discharge and detention time for treatment.

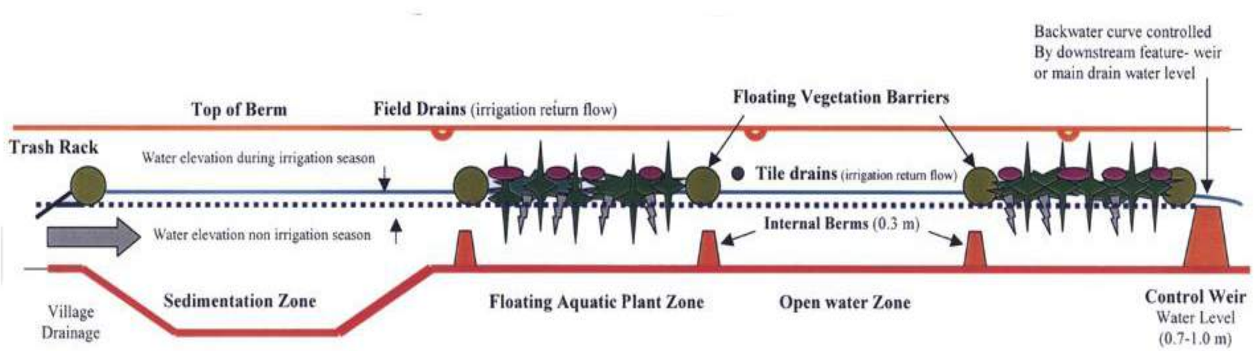


Figure 1: Profile view of an in-stream wetland treatment system

In-Stream Wetland Design Criteria

The design equation of wetland systems considers the environmental conditions especially the evapotranspiration losses since it affects on the large surface area of the basin. Also, filter media condition is taken into consideration. Therefore, the equations would be as mentioned as follows [Reed et al., 1988, Hammer, 1990].

$$\frac{C_e}{C_i} = 0.52 \exp\left[-\frac{0.7\, K_t\, (A_v)^{1.75}\, L\, W\, d\, n}{Q}\right] \quad (1)$$

$$K_t = 0.0057\,(1.1)^{T-20} \quad (2)$$

Where:

C_e = effluent BOD (mg/l)

C_i = influent BOD (mg/l)

K_t = the rate constant at water temperature (day^{-1})

A_v = specific surface area for microbial activity (m^2/m^3)

n = porosity of system (decimal fraction)

T = temperature (^0C)

L, W, d = length and width of pond at surface water and depth (m)

When the bed slope or hydraulic gradient is equal to 1 percent or greater it is necessary to adjust the equation to:

$$\frac{C_e}{C_i} = 0.52 \exp[-\frac{0.7\, K_t\,(A_v)^{1.75}\, L\, W\, d\, n}{4.63\, s^{1/3}\, Q}] \tag{3}$$

The next assumptions will be used as design criteria for the free water surface wetlands:

- The specific surface area (A_v) for attached microbial growth = 15.7 m^2/m^3
- Porosity (n) of wetland flow path = 0.75
- Aspect ratio (L/W) > 10:1
- Water depth in warm months < 10 Cm and in cool months < 45 Cm

Then the hydraulic residence time will be as follows:

$$t = \frac{(\ln C_i - \ln C_e) - 0.6539}{65\, K_t} \tag{4}$$

If the bed slope or hydraulic gradient is equal to 1 percent, then

$$t = \frac{(\ln C_i - \ln C_e) - 0.6539}{301\, s^{1/3}\, K_t} \tag{5}$$

The surface area of the wetland is given by

$$A = \frac{Q(\ln C_i - \ln C_e - 0.6539)}{65\, K_t\, d} \tag{6}$$

And if the bed slope or hydraulic gradient is equal to 1 percent, then

$$A = \frac{Q(\ln C_i - \ln C_e - 0.6539)}{301\, s^{1/3}\, K_t\, d} \tag{7}$$

Selection of Pilot Area

To evaluate the suggested alternative drain sites for in-stream wastewater treatment, several criteria have been adopted. These criteria reflect the diversity of the issues and dimensions associated with the in-stream wastewater treatment. Three main categories are used to evaluate the alternative sites: the drain conditions, water quality input to the drain, and the area's community. Under each category, few selected sub-criteria are considered. That selection of the sub-criteria is based on relevance, data and possibility of quantification. The selected sub-criteria are:

- ***Drain Type:*** A tertiary open agricultural drain that managed by Ministry of Water Resources and Irrigation. So, any physical required intervention on the drain can be implemented.
- ***Physical Condition of the Drain Cross-section:*** A well-formed drain cross-section, with regular bed, berms and banks is very important, in addition to the existence of sufficiently wide side-road(s) for vehicle accessibility.
- ***Accessibility:*** The selected reach of the drain must have no physical objects that may obstruct accessibility and/or equipment movement. Infrastructure facilities on the drain banks or side roads.
- ***Population and Pollution Load:*** A small rural community should exist very close to the drain.
- ***Wastewater Disposal Location and Disposal Point:*** The municipal wastewater effluent should be dumped at the selected drain through limited point sources.
- ***Absence of Industrial Wastes:*** It is highly important that no industrial activities take place at the selected rural community to avoid any disposal of industrial wastewaters to the drain, which may include toxic substances affecting the biological process.
- ***Community Appreciation and Acceptance:*** The local governorate, municipalities and the community will have no objection for construction of in-stream treatment system.

A maximum score has been assigned to each of the selection criteria indicators such that the total maximum score is 100 points to make the comparison among the total scores of potential drain sites. It can be concluded from the analysis that the selected drain “Bahwo drain” meets most of the selection criteria with score of 95%. The total drain length is about 2 km with area served 1,270 feddans of agricultural lands and drainage water duty of 30 m^3/feddan/day.

Baseline Studies for the Selected Site

Baseline studies include the fieldwork and data collection such as site detailed investigations and monitoring activities. The major tasks implemented under the baseline studies phase are presented in the following sections.

Drain physical survey and land-use survey

The selected drain is surveyed in order to build the topographic map for the area (land terrain, boundaries, and natural features). This will include the geometric survey of the selected secondary drain itself (width, bed level, slopes, … etc.). Other investigations will also be made including but not limited to: soil classification, drainage conditions, cropping pattern, and irrigation technologies used. Land-use is defined (agricultural lands, roads, industrial facilities, trees, rural areas, villages and community areas, … etc.) in terms of: areas occupied, nature of activity, crop rotations, irrigation water requirements, population density, and geographic location.

Socioeconomic survey

The community's characteristics including but not limited to: population, profession, degree of education, health care level, social facilities and services offered in the community, traditions, and transportation will be addressed. In addition, the water supply quantities used and sewage water released (quantities and qualities), and types of wastewater disposal methods (sanitation system or septic tanks) will be identified.

Subsurface water level

The subsurface water is monitored through a group of observation wells constructed at three sites; residential area, fallow land and agriculture land. Each site has three observation wells and the level is measured daily.

Drain flow

Flow measurements at downstream reaches of the drain are conducted weekly and level recorder is installed with several staff gauges to monitor the drain water level continuously.

Quality

A quality monitoring program was designed and implemented for sampling drainage water and sediment in the selected drain. The monitoring scheme covered the period of a year and four sites along the drain. Water sampling frequency was bimonthly at each of the monitoring sites as indicated in Figure (2).

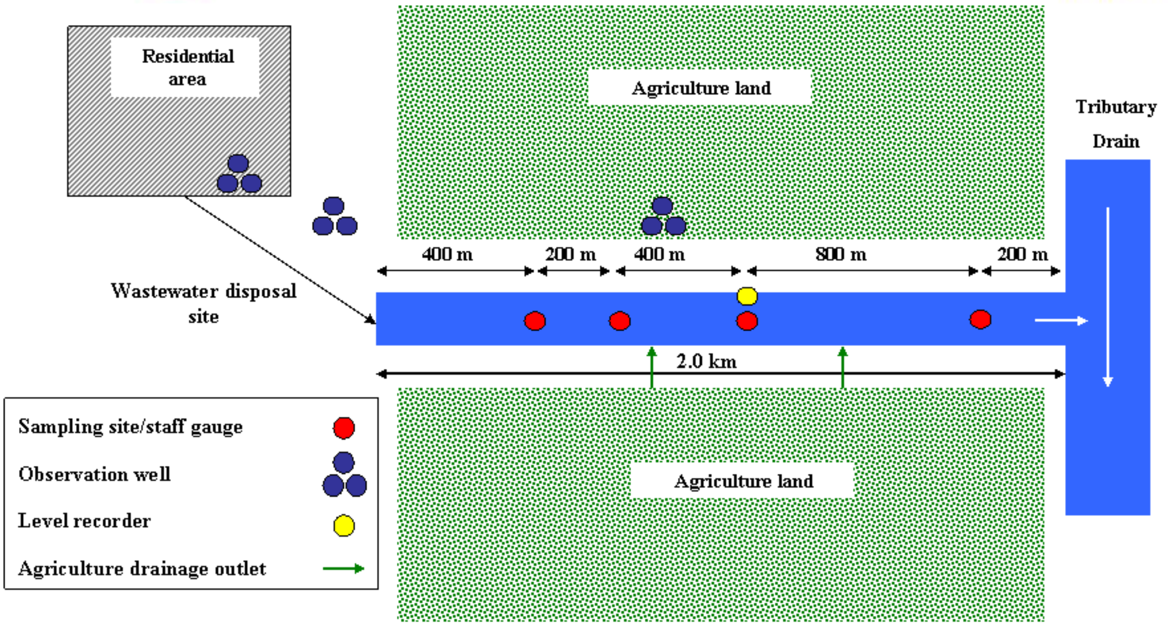


Figure 2: Schematic diagram for the monitoring scheme along the study area

Analysis of Baseline Data

Flow

A relation between flow and drain water depth with satisfactory correlation coefficient has defined. The minimum and maximum flows are found to be 0.018 m^3/s and 0.08 m^3/s and the corresponding water depths are 0.15 m and 0.4 m respectively.

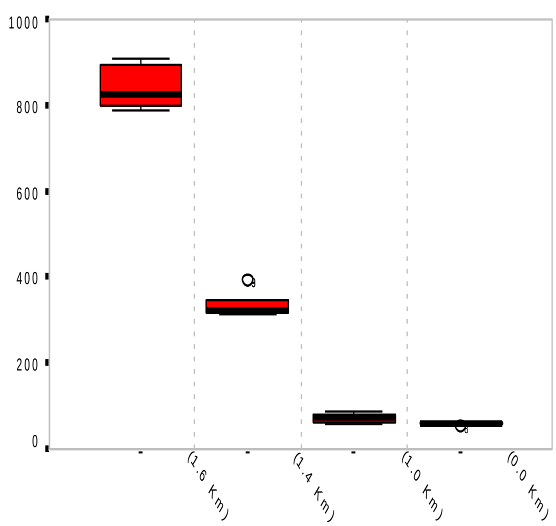
Subsurface Water Level

There is remarkable difference in subsurface water table for the three monitored areas where the subsurface water level at residential area is almost stable and varies around 2.0 m. The subsurface water level should not reach 1.5 m below the ground surface to avoid any impact on the house's foundations. The subsurface water at the fallow land, which is located between the residential area and the agriculture land, varies in narrow range between 1.3 m to 1.7 m below ground surface. The subsurface water at the agriculture land varies in wide range between 0.5 m to 1.5 m below ground surface depends on the irrigation period. The variation almost has the same pattern. The drain water level should not any way reach the subsurface water table at the agriculture land after operation of the wetland system to avoid any water logging.

Quality

The conducted monitoring program includes physical, chemical, biological and heavy metals parameters. The following section focuses on critical parameters which are considered matter of concerns during the wetland system design process including DO, BOD/COD, TSS, fecal bacteria and TDS.

The upstream reach of drain is subject to anoxic condition where the untreated domestic waste from residential area is discharged. Further downstream, DO levels of the drainage water is changed to be aerobic around 2.0 mg/l to 3.5 mg/l at 1.2 km and 1.8 from the upstream site respectively. The BOD values reach the maximum values further upstream of the drain (about 900 mg/l) and decrease to about 300 mg/l after 600 m to reach the minimum level at the drain outfall (80 mg/l) as shown in Figure (3). Remarkable reduction in organic waste takes place at the upstream reach which functions as sedimentation chamber. Further improvement is due to dilution with agriculture drainage water in the downstream reaches. The same conclusion is valid for COD and TSS (Figure 4) and follows the same pattern of BOD where the sedimentation is the dominant process. Nitrate is found to be below 1.0 mg/l and increases in the downstream direction to reach 6.0 mg/l while Ammonia is decreases in the downstream direction due to nitrification and denitrification process. Pathogens indicated by fecal bacteria are found to be extremely high further upstream reach of the drain at wastewater damping site (about $2*10^6$ MPN/100ml) and subjected to remarkable decrease in the down stream direction to be about $20*10^4$ MPN/100ml. The TDS is stable and varies in narrow range down stream reaches where more drainage water is mixed with the wastewater. The TDS upstream values vary between 1500 to 2500 mg/ and is reduced downstream varying between 1000 mg/l to 1500 mg/l. The heavy metals presented in drainage water samples are within allowable limits according to national law (48/82) and FAO recommended guidelines for reuse in agriculture.



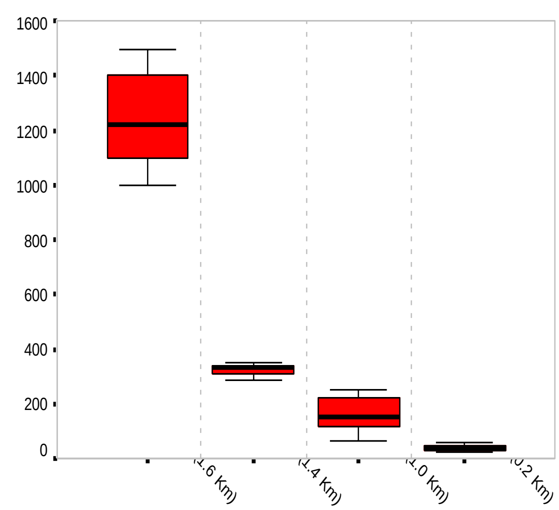


Figure 3: BOD levels along the drain

Figure 4: TSS levels along the drain

Simulation Tools

HEC-RAS Package

HEC-RAS is an integrated system of software developed by US-Army Corps of Engineers designed for interactive use in a multi-task environment (USA Army, 2002). HEC-RAS system contains one-dimensional hydraulic analysis components for steady and unsteady flow water surface profile computations. These components are intended for calculating water surface profiles for steady and gradually varied flows. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated from Manning's equation and the consideration of contraction and expansion form losses. The effects of various obstructions such as bridges, culverts, weirs, and in-stream structures may be considered in the computations. The steady flow system is designed for application in assessing the change in water surface profiles due to different channel improvements. HEC-RAS has also the advantage of considering vegetation induced the surface resistance.

MATLAB Package

The HEC-RAS package does not contain a module to simulate the transport of different pollutants and substances such as TSS or BOD. Therefore, it was necessary to build an external transport module to simulate the convection, diffusion and decay of pollutants. This is done within the environment of MATLAB package. MATLAB (**Mat**rix **Lab**oratory) is an interactive software system for numerical computations designed for matrix computations: solving systems of linear equations, computing eigen-values and eigen-vectors, factoring matrices, and so forth. MATLAB is designed to solve problems numerically, that is, in finite-precision arithmetic (David F, 2001).

Hydrodynamic Simulation Process

The proposed typical elements of the PIW channel consist of three main zones. The first zone is sediment trap proposed for the collection of deposited suspended particles. The sediment trap zone is followed by two floating aquatic plant zones separated by an open water zone. The objective of the floating aquatic plant zones is to make use of the aquatic plants to take up nutrients and to support microorganisms that can convert them and other pollutants into less harmful forms. Each zone is separated by internal baffles and/or an end weir.

Different Design Scenarios

In order to understand the hydrodynamic effects of each element in the typical PIW channel system, a group of 25 numerical runs have been proposed as listed in Table (1). In each run, one or more variable is/are changed, as given in the table. The listed runs can be reclassified into sets of runs as follow:

Without aquatic plant

This set of runs includes runs 1 to 3 where no aquatic plants or open water zones are considered in the simulation. The first run is considered as the basic run where the actual surveyed bed profile of the pilot drain is used in the simulation. The second run assumes a modified smoothed bed profile. The third run considers the effect of having a sedimentation zone 400 m in length and 50 cm in depth.

Set 2: With weir or baffles

This set of runs includes runs 4 to 10 and considers the effect of having a sedimentation trap zone and one weir on the hydraulic performance of the system. No aquatic plant zones are considered in this set.

Set 3: With aquatic plant

This set of runs includes runs 11 and 12 and is the same as those of run 10 except that immersed plants are considered in the analysis. For run 11, immersed plants are assumed to cover the first aquatic zone only whereas run 12 assumes the existence of immersed plants in two reaches.

Set 4: Typical PIW

This set of runs includes runs 13 to 22. The conditions of this set of runs are the same as those of set 3 except that floating aquatic plants replace the immersed plants at the positions indicated in the table. The floating plant thicknesses and roughness are given in the table.

Set 5: Variable discharges

This set of runs includes runs 23 to 25 and is similar to those of set 4 but with different discharge flux. The objective of this set of runs is to check system response to discharge variability.

Results Summary

Based on the aforementioned results listed on Table (1), it can be concluded that:

- The end weir plays the most important role in controlling the detention time throughout the PIW channel system. The higher the crest of the end weir the longer the produced detention time of the system.
- Interior baffles do not have significant effect on the produced detention time of the system.
- Aquatic floating plants have small effect on the produced detention time. It is found that, as the thickness of the aquatic floating plants gets bigger and or the plants' aerial density gets higher, the detention time gets longer.
- Also, it has been noticed that discharge variation has a nonlinear response to the detention time. For example, an increase of 50% in Q will cause the detention time to decrease by 36% whereas a decrease in Q by 50% causes the detention time to increase by 91%.

Table (1): List of numerical runs and calculated detention time

Run	Q%	Depression	Weirs height (cm)		Baffles height (cm)		Vegetation		Time (hr)
			A	D	B	C	A→B	C→D	
1	100%	No							
2	100%	No							9.29
3	100%	Yes							12.92
4	100%	Yes	30						14.46
5	100%	Yes	50						24.43
6	100%	Yes		30					14.66
7	100%	Yes		50					30.8
8	100%	Yes		75					66.55
9	100%	Yes	50	50					35.11
10	100%	Yes	50	50	25	25			35.11
11	100%	Yes	50	50	25	25	n=.06		35.11
12	100%	Yes	50	50	25	25	n=.06	n=.06	35.54
13	100%	Yes	50	50	25	25	n=.03, t=5 cm		33.78
14	100%	Yes	50	50	25	25	n=.03, t=5 cm	n=.03, t=5 cm	34.06
15	100%	Yes	50	50	25	25	n=.02, t=5 cm	n=.02, t=5 cm	33.85
16	100%	Yes	50	50	25	25	n=.01, t=5 cm	n=.01, t=5 cm	33.7
17	100%	Yes	50	50	25	25	n=.01, t=10 cm	n=.01, t=10 cm	35.14
18	100%	Yes	50	50	25	25	n=.02, t=10 cm	n=.02, t=10 cm	35.3
19	100%	Yes	50	50	25	25	n=.03, t=10 cm	n=.03, t=10 cm	35.51
20	100%	Yes	50	50	25	25	n=.03, t=20 cm	n=.03, t=20 cm	45.01
21	100%	Yes	50	50	25	25	n=.02, t=20cm	n=.02, t=20cm	44.56
22	100%	Yes	50	50	25	25	n=.01, t=20cm	n=.01, t=20cm	44.23
23	100%	Yes	50	50	25	25	n=.02, t=10 cm	n=.02, t=10 cm	19.19
24	150%	Yes	50	50	25	25	n=.02, t=10 cm	n=.02, t=10 cm	24.35
25	50%	Yes	50	50	25	25	n=.02, t=10 cm	n=.02, t=10 cm	68.66

Transport Modeling Results

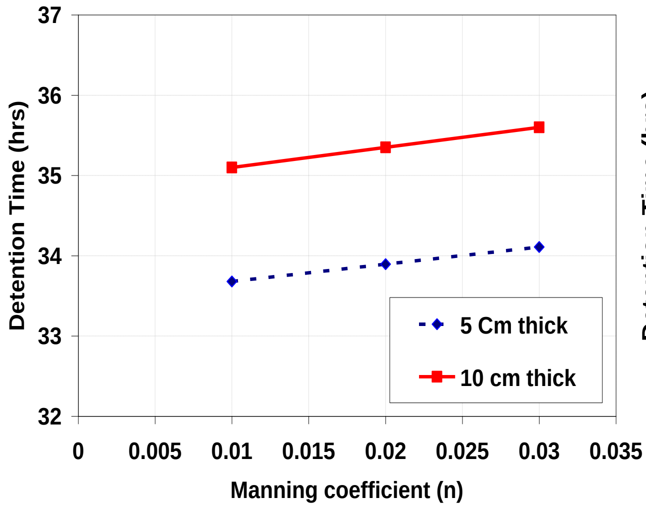


Figure 6: Vegetation response to detention time

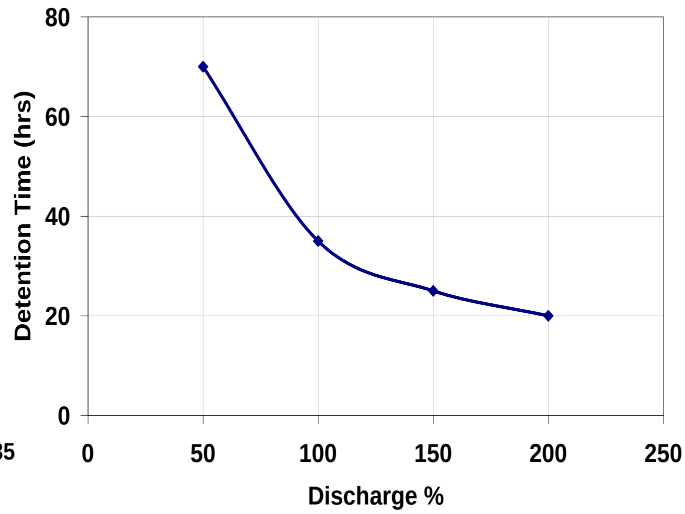


Figure 7: Effect of discharge variation on detention time

Simulation of TSS Transport

The spatial variation of the total suspended solids can be obtained by applying a sort of transport equation that includes the advection, diffusion and decay terms. The governing equation is a second order parabolic of the following form (Reed et al., 1988, Hammer, 1990):

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} - w_s\frac{\partial C}{\partial z} = D_x\frac{\partial^2 C}{\partial x^2} + D_2\frac{\partial^2 C}{\partial x^2}$$

Where:

C = TSS concentration

U = downstream convection velocity

Ws = settling velocity of the suspended particles

Dx, Dy = diffusion coefficients in the x and y directions

In order to solve the previous equation, an explicit finite difference MATLAB code has been written. By using the aforementioned code, it was easy to determine the settling length for different soil classification. It is clear that the sedimentation trap zone length should not be less than 400 m.

Simulation of BOD Transport

Because the pilot drain receives untreated sewage water besides the agricultural water, it is of interest to simulate the decay/growth of the biological oxygen demand which is considered as the most important parameter for describing the quality of wastewater. BOD removal efficiency of the system could be obtained by solving the BOD transport equation (Reed et al., 1988, Hammer, 1990):

$$\frac{d(BOD)}{dt} + \frac{ud(BOD)}{dx} = -k(BOD)$$

Where:

BOD = biological oxygen demand concentration

U = local velocity of the system obtained from the hydrodynamic part

K = decay coefficient

An explicit finite difference MATLAB code has been written to solve the previous equation to determine the removal efficiency of the typical design scenario. Moreover, sensitivity analysis of the decay coefficient has been conducted to measure the effect of uncertainty in k on the BOD removal efficiency as presented in Figure (7).

It is noticed that the average BOD removal efficiency is about 65%. It is also clear that the results are sensitive to the decay coefficient value as an increase of 25% in k resulted in a variation of 22.5% in the outlet BOD.

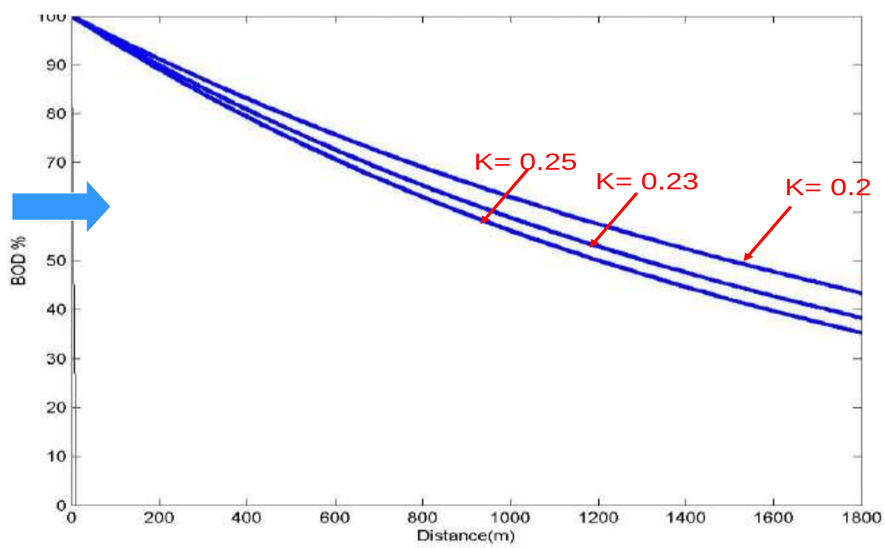


Figure 8: BOD spatial decay along the drain pilot

Fecal Transport and Decay/Growth Simulation

The survival of Fecal Coliform (FC) in an aquatic environment depends upon their ability to tolerate a set of alien biological, physical and chemical conditions. The most important factors that control the rate of decay are temperature, solar intensity, and pH (Auer and Niehaust, 1993). In order to consider the spatial variation of the fecal concentration in addition to the time response, a mathematical model based on the traditional advection-diffusion equation is adopted. The model governing equation is given by the following equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[Dx \frac{\partial C}{\partial x} \right] - u \frac{\partial C}{\partial x} + \sum_{z=1}^{np} r_z$$

Where:

C	=	FC count (MPN/100 ml)
t	=	time (day)
x	=	longitudinal distance (m)
u	=	average speed in the x direction (m/d)
r_z	=	term describing each one of the physical, chemical or biochemical processes responsible for modifying the polluting concentration (MPN/100 ml/d)

The spatial variation of FC with the distance downstream for two different values of the decay rate of 1.2 and 0.4 day^{-1} have been selected to cover the expected range of k. It has been noticed that the FC count is highly sensitive to the assumed value of k and the expected removal efficiency of FC is from 40% to 70%.

Pilot Area Drain Design

Based on the aforementioned results of the hydrodynamic simulation and the transport analysis, it is proposed to carry out the following steps to modify the drain to work as in-stream wetland treatment scheme.

Reformation of Drain Bed Profile: The bed profile of Al-Bahoo drain is proposed to be smoothly reformed to form the sedimentation trap. The sedimentation trap is proposed to extend from the drain inlet (Station: 1+720) to (station: 1+200) with a length of 520 m. The sedimentation trap needs to be rehabilitated and maintained regularly (minimum rate of reformation and excavation is bimonthly). A nearby area of about 0.5 acre should be allocated for the project to receive dredged sediment from the sediment trap.

Planting of Aquatic Plants: Two types of aquatic plants are proposed; the first type is the phragmites to be implanted downstream of the sedimentation zone between stations (8+50) and (7+50). The second type of plants is the water Hyacinth and it will be used 185 m downstream of the aforementioned aquatic zone between stations (6+50) and (5+50). A trash screen at station (5+50) is highly recommended to control the booming of water Hyacinth and regular maintenance is still required.

End Weir: The end weir plays the most important role in controlling the detention time throughout the in-stream wetland channel system. Since the water level of the drain is expected to vary with the time, it is proposed to build an adjustable-crest end weir. The weir consists of a 25 cm sill and a number of timber logs (5 logs) each of height 10 cm. In case of fixing all the logs, the total weir height reaches 75 cm. The proposed system is provided with a cheap lifting system for fixing/removing logs in accordance with the situation and the need.

Detention Time: It is important to estimate the expected detention time of the proposed system considering the aforementioned details. Therefore, a final run using HEC-RAS has been conducted and the detention time was found to be 3.0 to 5.0 days (considering the full height of the end weir).

Conclusions

The detention time has been selected to be a critical design criterion for in-stream wetland channel systems. The higher the detention time the better the quality of the effluent water. The study proposed different design alternatives. The detention time could be significantly increased from its typical current value of 6-8 hrs to more than 68 hrs (about 3 days) by using simple elements (such as sedimentation trap and end weir).

After examining the significance of each element (sedimentation trap, end weir and baffles) in the typical arrangement, it has been found that:

- The end weir plays the most important role in controlling the detention time throughout the PIW channel system. The higher the crest of the end weir the longer the produced detention time of the system.
- Interior baffles do not have significant effect on the produced detention time of the system.
- Aquatic floating plants have small effect on the produced detention time. It is found that, as the thickness of the aquatic floating plants gets bigger and/or the plants' aerial density gets higher, the detention time gets longer.
- The discharge variation has a nonlinear response to the detention time. An increase of 50% in Q will cause the detention time to decrease by 36% whereas a decrease in Q by 50% causes the detention time to increase by 91%.

The preliminary computational results of this study showed that a removal efficiency of 60% for BOD could be easily achieved using the proposed design arrangement. Moreover, the preliminary analysis found that the expected removal efficiency for the Fecal Coliform is expected to reach 70%. The proposed in-stream wetland requires at least a bimonthly removal of deposition material from the sediment trap. A reduction of the efficiency of the system might take place if the depositions are not regularly removed.

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ENVIRONMENTAL CAPABILITIES AND CONSTRAINTS OF HALOCULTURE: ALTERNATIVE STRATEGY TO USE SALINE WATERS IN MARGINAL LANDS

Farhad Khorsandi[1,*]

Abstract

Disposal of saline agricultural wastewaters is a complex environmental challenge for agronomists and irrigation managers. The rise in world population, shortage of premium agricultural lands, and scarcity of fresh water resources, particularly in arid regions, makes it necessary to use non-conventional saline water resources and marginal lands to meet the escalating demand for food and drinking water needs. Haloculture offers a strategy for sustainable use of highly saline soil and water resources to provide some of the future human needs. Haloculture is sustainable production of different agricultural and industrial products in saline environments. A saline agricultural drainage water Haloculture agro-industry model is presented, which serves as an economic option for their reuse, and thus, reducing their negative environmental impacts. Along with development of strategies for sustainable and profitable production of bio-products, Haloculture also emphasizes on providing energy and drinking water as the basic needs of rural societies who are going to implement those strategies in less developed, salt affected regions. Haloengineering is briefly introduced as a complementary component of Haloculture. Various activities in Haloculture depends on the input of waters with different salinity levels. Thus, a new guideline for utilization of saline waters in Haloculture is presented. Several cases of Haloculture projects with various degrees of success and failure operated nationally and internationally. The mega project on Haloculture undertaken by Iran Water and Power Resources Management Company in four southern coastal provinces of Iran, are described in more details. Haloculture is recommended in areas where conventional agriculture is not physically and/or economically feasible. Environmental stewardship is an important component of a sustainable production system. Thus, the main objective of this article to evaluate the environmental services and constrains of Haloculture. Haloculture has significant environmental potentials in salt-affected arid regions, in terms of combating desertification and erosion, sustainable use of agro-biodiversity, restoration of rangelands, remediation of degraded lands, and greening of coastal areas, reforestation of marginal and degraded lands, restoration and rehabilitation of wildlife and marine habitats, and carbon sequestration. Possible environmental constraints of Haloculture should be considered in development of Haloculture projects. The main possible negative impacts of Haloculture on environment are escalating soil salinity, introduction of invasive exotic plant and aquatic species, degradation of local ecosystem, and possible adverse effects of saline water irrigation on ground water quality. Development of Haloculture projects in previously undeveloped inland salt affected regions and coastal zones, should be done with thorough ecological and environmental impact assessment.

KEY WORDS: Biosaline agriculture, Desalination, Drainage waters, Haloengineering, Halophyte, Haloventure, Saline aquaculture, Seawater agriculture

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Introduction

Management and disposal of saline agricultural wastewater, consisting mainly of saline water from drainage projects, aquaculture ponds and desalination plants, has always been a critical social and environmental challenge for agronomists and irrigation managers. Reusing saline wastewater resources for crop irrigation and saline aquaculture activities as a means of their disposal and the conservation of fresh water supplies for other activities, has been of interest for decades, particularly in arid regions and when other water supplies become scarce during a drought (Grismer and Bali, 2015). Many wheat farms in the southern regions of Khuzestan, Iran, are irrigated using saline drainage water (4-15 dS/m) directly or in combination with fresh water, to reduce the impacts of drought stress on wheat (Akbari Fazli et al., 2013).

Saline agricultural wastewater and other saline water resources (i.e. seawater, saline surface and groundwater resources) are considered as non-conventional water. Non-conventional water is defined as water that possesses certain characteristics which have the potential to cause problems when used for an intended purpose (Pescod, 1992). Therefore, the use of non-conventional water requires the adoption of more stringent and prudent environmental management practices and monitoring procedures. The use of highly saline water, unusable by common agricultural crops may be feasible for the production of halophytes, which could be utilized for human and animal consumption, as well as, the production of other useful products such as algae, saline aquaculture and energy. This will make them as a valuable resource rather than a waste product.

According to FAO statistics, global food production needs to increase up to 70% by 2050 to ensure adequate and safe access to food to a burgeoning population (Panta et al., 2014). This is also true for arid and semi-arid regions, where fresh water resources are scarce and are in high demand for urban consumption. Since most of the productive soils are being used for agricultural production and with the rise in inter-sectoral competition between agriculture and other segments of the economy, there is little scope for agricultural expansion in prime lands (Qadir and Oster, 2004).

About 950 Mha of land surfaces and 50% of irrigated lands (230 Mha) are affected by salt intrusion globally (Ruan et al., 2010). In addition, out of 1386 million cubic kilometers of total world water resources, less 1% (about 10.6 million cubic kilometers) are actually available for human use. The rise in world population, will also put more pressure on available good quality water resources, to meet the escalating demand for urban use and drinking water needs. It is believed that the need for increased food production cannot be achieved merely by cultivating the currently available arable lands (Shabala, 2013). Consequently, using marginal lands, such as salt affected lands, and alternative water resources, such as saline water, for agricultural production, is an inevitable option to attain human food requirements in the future. Therefore, it is necessary to expand the utilization of more salt tolerant plants, particularly halophytes, and livestock that can tolerate saline drinking water and halophyte forages, such as those for camels, as well as, expanding saline aquaculture to provide necessary human food supplies in the future.

The cultivation of salt tolerant crops and halophytes is seen as a practically feasible and economically viable option for utilizing saline soil and water resources, and conserving fresh water for other much needed purposes (Glenn et al., 1998, 1999; Ladeiro, 2012; Ventura and Sagi, 2013; Panta et al., 2014; Agnihotri and Kumar, 2015; Sharma and Singh, 2015; Ventura et al., 2015). Under these circumstances, the need for a technology that is practical, and which requires low inputs in addition to it being sustainable in the long run becomes imperative. *Haloculture* is an important option under such conditions. Environmental integrity and stewardship is an important aspect of sustainability. Thus, the main objective of this article is to evaluate the important environmental services and constraints of Haloculture as an integrated system for the productive use of saline soil and water resources.

Principles of Haloculture

Haloculture is proposed as a holistic approach for (i) the sustainable management and utilization of saline soil and water resources for increased agricultural production, (ii) the combating the damage caused by desertification, erosion and dust storms, and (iii) the creation of employment opportunities and socio-economic improvements in less developed regions. Haloculture is defined as the sustainable production of different agricultural and industrial products in saline environments (Fig. 1). Agricultural products include diverse output from plant (agronomic, horticultural, forestry, range, ornamentals and medicinal plants), animal (small and large livestock, poultry, honey bees, etc.) and aquaculture (fishes, shrimps, seaweed, algae, artemia, halophiles, etc.). Similarly, industrial products refer to processed forms of the agricultural products as well as the production of water, salt and energy. Genetic biodiversity is the key to the productive use of saline environments. It includes plants, animals and microbial resources that can be grown in saline lands and/or aquatic environments. Due to significant differences in agro-climatic conditions, Iran boasts a rich genetic diversity of crops, animals and microorganisms for profitable Haloculture under varying saline conditions in different geographic locations. The availability of diverse potential resources- either individually or in combination with each other- literally means a diversified Haloculture. Based on empirical evidence regarding the shortcomings of crop monocultures (Hennessy, 2004; Suárez and Emanuelli, 2009), it is always desirable to have an integrated Haloculture production system. This will enable the efficient use of the available resources and will minimize the risks caused by adverse conditions (e.g., extreme climate events) by enhancing the resilience of the system (Hendrickson et al., 2008; Manjunatha et al., 2014).

The salt-affected water resources that can be used productively, include saline surface and ground water, sea water, agricultural drainage water and discharged effluents from saline aquaculture ponds and desalination plants. A Haloculture Agro-Industry Complex is called *Haloventure*. The first phase of a Haloventure starts with saline aquaculture through fish, shrimp and/or algae. The water discharged from aquaculture is used for halophyte production of various types. In fact, halophytes are regarded as new agronomic crops in Haloculture with various economic uses (Fig.

1). Most often, the salinity of such lands is too high for the economic production of conventional agronomic crops. The drainage water from halophyte fields, which has more salinity than the water used in previous phases, may be collected and reused in hypersaline aquaculture activities, such as artemia and highly salt tolerant microalgae production. The highly saline water or brine discharged from this phase should be disposed properly in order to make it economically useful, and more importantly prevent environmental damages. The economic activities in this phase may include salt and mineral harvesting (Ahmed et al., 2000, Surinaidu et al., 2016) or producing energy using salinity gradient solar ponds (Malik, 2011, Saifullah et al., 2012).

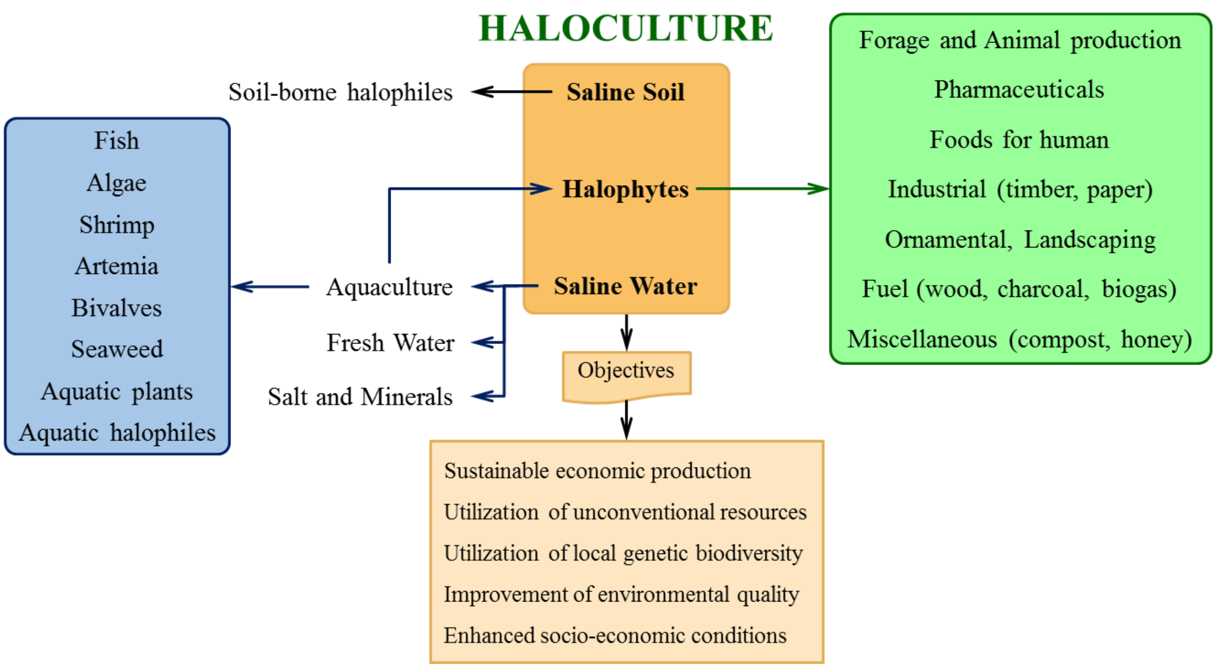

Figure 1. Schematic representation of the principals and objectives of Haloculture.

Haloculture in practice

Haloculture integrated production system may be practiced as Haloventure in saline lands by using high salinity water in coastal areas available from seas and oceans. Brines discharged from coastal desalination plants can also be a viable resource in those areas. Inland Haloventure projects in saline inland areas may also be practiced using inland saline water resources, especially saline agricultural drainage water (Fig. 2). The installation of drainage systems in halophyte farms will greatly contribute to the sustainability of the project by preventing the salt load on those farms to rise above the salt tolerance of the highly salt tolerant and halophyte plants.Moreover, it also contributes to the sustainability, economic profitability and environmental stewardship of inland

Haloventure projects, by providing additional saline water resources to be used for various economic activities, rather than contaminating ground and surface water resources (Fig. 2).

Salt water aquaculture and mariculture has been widely practiced, and is a prime example of the economic utilization of saline water resources throughout the world. Traditional livestock producers have used halophyte forages for their herds, particularly during winter season when there is a shortage of forages. Indigenous tribes, particularly in Australia and the American continent, have consumed halophytes as fruits and vegetables, as well as for fuel and as building material. It seems that in the last two decades, the commercial production of halophytic vegetables has grown, particularly in Europe, where there is a market for such products inserted in the population's diet. Several companies specialize in the production of sea vegetables, such as Salicornia, sea fennel, salsola, sea kale, sea aster and sea beet in Belgium and the Netherlands. Australian livestock industry use halophytes extensively for grazing their cattle. The use of halophytic forages has also grown in Pakistan and India in the last decade.

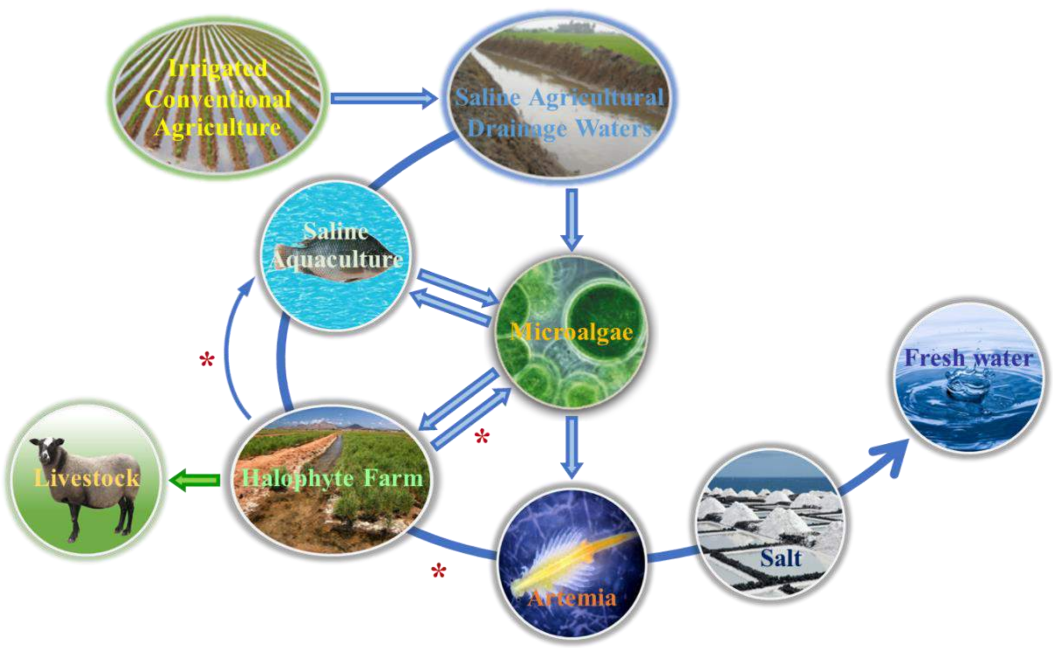

Figure 2. Example model of inland Haloventure with saline agricultural water (>12 dS/m).

Several Haloculture projects with varying degrees of success and failure have operated internationally. Examples are given below.

International projects

Manzanar Project, Eritrea: Manzanar Project, ongoing since 1987, is one of the oldest and most successful non-profit Haloculture projects, which was implemented by an American scientist in

Eritrea (Sato, 2009). The main goal of this simple and low-technology project was purely humanitarian. Manzanar Project aims at utilizing seawater for coastal mangrove plantations by local poor-resource farmers, who use them as a sustainable source of forage for their goat herds. As a side benefit, mangrove plantations have improved the marine ecology at the seacoast, thus producing extra fishing opportunities for the farmers as well.

Integrated Seawater Agriculture System, Eritrea: Seawater Foundation was one of the active companies in the sequential utilization of sea water for various products, known as Integrated Seawater Agriculture System (ISAS). They started their first seawater farm in Eritrea in the year 1998, producing shrimp, Salicornia and mangroves (Bailis and Yu, 2012). The farm, however, was shut down after 5 years in 2003 due to political instability within the government of Eritrea.

Integrated Seawater Agriculture System, Mexico: The second seawater farm was established in Bahia Kino, Mexico, with the aim of producing Salicornia for biofuel, as well as, shrimp and mangroves. The activities in Bahia Kino seawater farm was stalled in 2010 due to mismanagement and community opposition (Bailis and Yu, 2012).

Organization for Agriculture in Saline Environments, the Netherlands: Organization for Agriculture in Saline Environments (OASE) is the offspring of a successful and logical collaboration between the government of Netherlands and the private investment sector. The Ministry of Agriculture, Nature and Food Quality of the Netherlands completed a feasibility study on Haloculture in 2000. They designated their priorities as halophyte production for renewable energy and food, biochemical extraction and salt water aquaculture (van Oosten and de Wilt, 2000). Consequently, OASE was established in 2005 and have been successfully active internationally since then. They are operating projects in the saline coastal areas of Mexico's Baja California and the Colorado Delta on halophyte food and fodder production, as well as, Biosaline agroforestry in saline wastelands for energy, wood and charcoal.

The Sahara Forest Project, Qatar: More recently, a Norwegian based company has started The Sahara Forest Project, an ambitious sea water project, in the deserts of Qatar. The main objective of the project is the profitable production of food, water, clean electricity and biomass in desert areas (The Sahara Forest Project Foundation, 2013). This project also uses seawater for the integrated production of desalinized water using a Concentrated Solar Power system, saltwater-based greenhouse crops, halophytes, microalgae and salt.

Integrated Multi-Trophic Aquaculture, China: An integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China, is a very interesting and a prime example of large scale, integrated marine aquaculture production system utilizing sea water (Fang et al., 2016). This project produces more than 240000 tons of assorted seafood annually in an area of about 10000 ha, utilizing more than 30 marine species. This project seems to adhere closely to the basic principles of sustainability.

Haloculture practices in Iran

Various activities of Haloculture has been practiced in Iran mainly as separate economic ventures and not as an agro-industry complexes.

Saline aquaculture: Saltwater fish, shrimp and artemia productions have been common aquaculture activities in Iran over the past few decades, although, commercial artemia aquaculture is relatively new within the country. Seaweed and microalgae production in Iran, as well as their processing for bio-products, have been successful at research and laboratory levels in recent years. The management of nutrient rich and highly saline discharges from aquaculture, particularly from shrimp farms in the Southern coast of Iran, is an important environmental issue and concern. This problem could be properly managed if they are used for irrigated halophyte cultivation and/or microalgae and artemia productions.

Halophyte cultivation as a new agronomic crops: Commercial halophyte production is very limited in Iran, although, farmers in Borazjan (Boushehr Province) have been cultivating *Suaeda aegyptiaca,* known locally as *Kakol,* in highly saline lands and irrigating it with saline water. *Kakol* is highly popular in the South ofIran as fresh vegetables. Iran participated in the International Atomic Energy Agency (IAEA) interregional project INT/5/144 "Sustainable Utilization of Saline Groundwater and Wastelands for Plant Production" in 1997 (Pedraza, 2009). The project lasted for 6 years and was completed successfully in Chah Afzal, Yazd Province. The importance of this project was that for the first time in Iran, halophytes were considered and looked upon as possible new agronomic crops. Since then, the National Salinity Research Center of Iran has been involved with several international and national research projects with halophytes, particularly forage halophytes, over the last 15 years. However, the results did not lead to a commercial scale cultivation of halophytes yet. Nevertheless, ship, goat and camel shepherds have been traditionally using halophytes for grazing their herds for centuries.

Salt production from the brine outflow of desalination plants: Water desalination is gaining popularity, even among farmers, who suffer from extreme shortage of fresh water and high salinity of their water resources. Their main goal is not to produce drinking water, but to reduce the groundwater salinity to a level low enough for the irrigation of their crops. However, due to the shortage of drinking water and drought in many coastal regions of the country, mega scale desalination units are going to be constructed for the purpose of producing drinking water. Salt production has been practiced traditionally in various parts of the country for centuries. Salt production from discharged brine outflow of desalination plants may be a viable strategy for reducing the negative impact of the brine disposal to marine environments.

Haloculture mega project in Southern coastline provinces: More recently, a mega project on sustainable development of southern coastal zones utilizing Haloculture technology, has been proposed and started by the Iran Water and Power Resources Management Company (Ministry of

Energy). One of the major significances of this project is their multi-disciplinary and integrated approach to the issue. This Haloculture project aims at identifying appropriate places for the expansion of Haloculture agro-industrial complexes within four coastal provinces of Iran (Khouzestan, Boushehr, Hormozgan and Sistan and Balocestan) along the Persian Gulf and Sea of Oman coastlines. At the same time, 10 pilot farms and experimental projects have been proposed, some of which have already started. The pilot farms are engaged in Salicornia production as oil seed crops (both with sea water and shrimp farm saline discharges), and seaweed production in both seawater and shrimp farm discharge canals. This mega project will institutionalize Haloculture in Iran as a new integrated agricultural system, and plays and important role in the expansion of Haloculture among farmers and entrepreneurs.

Although various economic activities using Haloculture have been successfully practiced in Iran for many years, the holistic, integrated production system of Haloculture, or Haloventure per se, has yet to be implemented in the country. Iran has immense and extensive potential in the expansion of Haloculture. Environmental considerations will play a crucial role in the sustainability of Haloculture.

Environmental services of Haloculture

The types of lands intended for use in Haloculture are inland and coastal marginal wastelands, saline degraded lands, salt marshes and in general, t salinized lands that are not capable of producing economically conventional agronomic crops. Haloventure complexes might also be constructed in coastal areas that are heavily impacted by aquaculture or salt water intrusion due to groundwater abstractions, sea-level rise or other factors (Bailis and Yu, 2012). As previously mentioned, the cultivation of highly salt tolerant crops and halophytes is one of the most important activities in Haloculture. Halophytes can be used either for environmental purposes or for biomass production. The environmental benefits and services of Haloculture are enormous. A self-explanatory example of such services is presented for a halophyte tree cultivation program in highly saline lands of Chah Afzal area, Yazd (Fig. 3). Environmental benefits of Haloculture include:

- Combating desertification and soil erosion,
- Remediation of degraded lands (such as those contaminated by petroleum industries),
- Restoration of rangelands and greening of coastal areas,
- Reforestation of degraded salt-affected lands,
- Restoration and rehabilitation of wildlife and marine habitats, and
- Carbon sequestration and soil quality improvement through addition of organic matter, salt alleviation and soil structure improvement.

The High capability of halophytes for phytoremediation of heavy metal contaminated soils and saline soils has been demonstrated (Manousaki and Kalogerakis, 2011; Hasanuzzaman et al., 2014). Haloculture is also a practical method for the prevention of environmental damages that may be caused by the disposal of saline agricultural drainage water, nutrient rich water discharged from aquaculture farms, and saline and brine discharges from water desalination plants. Research results demonstrated that *Salicornia europaea* is an effective halophyte for biofilteration of saline wastewater from commercial marine fish and shrimp farms (Webb et al., 2012). Studies in South America showed that integrated production of fish + halophyte forage + livestock production is a successful scheme for turning the environmental problem of brine reject disposal in inland areas, to a productive agricultural activity (Sanchez et al., 2015).

The adverse effects of discharged saline agricultural wastewater on surface and ground water qualities, is an environmental concern in conventional agriculture. Haloculture offers a strategy for the successive reuse of saline agricultural water for the economic production of useful products, and thus, discourages the disposal of such water to surface water bodies. With the rapid development of desalination plants in arid regions, especially on coastlines, the discharge of hypersaline brines to the ocean has become an alarming environmental issue. Haloculture can be a viable solution to this environmental problem, particularly in coastal areas.

Environmental constraints of Haloculture

There may be some unintended environmental impacts of Haloculture that should be taken into considerations before initiating such projects. Secondary salinization of soils, introduction of invasive exotic plant and aquatic species, and the contamination of surface and ground water resources are the main environmental concerns about Haloculture. Haloculture is recommended in areas where conventional agriculture is not physically and/or economically feasible. Such areas include highly salinized agricultural lands, salt marshes, sandy coastal plains and deserts, and degraded desert lands with sparse vegetation. However, If Haloculture is going to be implemented in previously undeveloped coastal zones, then it could have negative environmental impacts (Bailis and Yu, 2012). Therefore, careful environmental impact assessment should be conducted under this condition.

Figure 3. An example of valuable environmental services of Haloculture: left- a barren saline land and right- a rehabilitated saline land through halophyte planting (Tamarix as windbreak and Haloxylon for wood) in Chah Afzal, Yazd Province, Iran (Pedraza, 2009).

It should be mentioned that sustainability and environmental considerations with due respect to Haloculture and other similar activities such as Biosaline agriculture or Seawater agriculture, emerge from the damages caused by irrigated agriculture. In fact, many of the irrigation projects throughout the world have inflicted huge damages to soil and environmental health. The fact that a great proportion of globally irrigated lands are currently severely affected by irrigation induced salinization is convincing evidence to this claim (Munns, 2005, Shabala, 2013, Sharma and Singh, 2015).

A legitimate concern about Haloculture, and in general regarding the use of saline water resources in agriculture, is secondary soil salinization. In fact, if natural soil drainage capacity is low, the continuous use of saline water for irrigation, may lead to high salt accumulations in the root zone, harmful to even salt tolerant halophyte plants. Sanchez et al. (2015) reported progressive salinization of the land irrigated with saline water discharges from inland desalination plants. Therefore, it is strongly recommended that in areas having restricted soil drainage, artificial drainage systems should be installed to ensure the sustained reuse of the saline drainage water in activities such as saline aquaculture, artificial wetlands or solar salt ponds.

The utilization of endemic biodiversity in various bio-production activities of Haloventure is highly emphasized in Haloculture. That is because they are naturally adopted to local climate and ecological conditions. In addition, local farmers are more familiar with native and local halophytes and their economic values and uses, and thus, are more willing to adopt those species for agronomic production. However, in some cases the utilization of exotic and non-endemic plant and animal species may be needed. In general, it is highly emphasized in Haloculture that the introduction of new plant and animal species from other regions or countries should be done with caution and under the advice of experts in the concerned field. In addition to considering invasive species, when constructing Haloventure projects, the developers must also consider conservation values and ecosystem function, buffer zones and ecological corridors (Bailis and Yu, 2012). This is especially true in previously undeveloped coastal areas.

The percolation of saline wastewater and highly saline irrigation water into ground water resources, adversely affects its water quality, and thus makes it a legitimate environmental concern, that is not only pertinent to Haloculture, but also to conventional agriculture as well. Halophyte farms irrigated with various saline water could be established based on three scenarios (a) farms with high levels of secondary salinization, (b) inland deserts situated on saline aquifers, and (c) coastal deserts and saline coastal plains. In the first case, soil physical and chemical characteristics should be evaluated to identify the reasons for the development of secondary salinization, in order to adopt the best management practices for the intended halophyte farms. In this case, the installation of drainage systems to collect and reuse the drainage water and prevent it from percolating to fresh water aquifers is highly recommended in this case.

The irrigation of halophytes with saline water on the farms situated above saline aquifers should not affect the water quality of the ground water significantly. That is because the saline water pumped for irrigation of the farms, is drained and goes back to aquifers that have been saline from the beginning. Studies done on saline discharges from desalination plants in Southern Arizona, United States (5% leaching fraction) revealed that these farms can be productively utilized through halophyte plants for at least 100 years without negatively affecting the groundwater quality more than conventional irrigated agriculture under the similar conditions (Riley et al., 1997). The soil texture of the intended halophyte farms in coastal deserts and plains is usually sandy and have adequate natural drainage capacity.

The irrigation of farms with highly saline seawater most likely should not impose an adverse effect on the ground water, because it will move back to the ocean again. Halophytes usually require less fertilizers than conventional crops, and seawater can provide most of the nutrients that they need. However, if farms require high nitrogen fertilizers, then it might contaminate the ocean and cause coastal microalgae bloom. There is an unresolved dispute between the Eritrean Department of Environment and Seawater Farms Eritrea (SFE) over the level of nitrogen and phosphorous concentrations in the effluents produced by SFE and its possible involvement in the occurrence of coastal algal bloom (Bailis and Yu, 2012). In this case, the installation of drainage systems to collect and reuse nutrient rich saline water from the farm for other economic or environmental activites is highly recommended.

Conclusions and recommendations

Haloculture has significant potentials in salt-affected arid regions, in terms of combating desertification and other environmental services, sustainable utilization of saline soil and water resources, sustainable use of agro-biodiversity, the creation of employment and income generation opportunities for the resource poor farmers, and improving the socio-economic conditions of communities in salt affected areas. Environmental integrity is one of the key issues in the sustainability of Haloculture. In addition it has significant environmental benefits, possible environmental constraints of Haloculture should be considered in the development of Haloculture activities. The main possible negative impacts of Haloculture on the environment are secondary salinization of soils, introduction of invasive exotic plant and aquatic species and degradation of local ecosystem, and possible adverse effects of saline water irrigation on ground water quality.

Haloculture is recommended in areas where conventional agriculture is not physically and/or economically feasible. However, the development and implementation of Haloculture projects in previously undeveloped inland salt affected regions and coastal zones, should be done after a thorough ecological and environmental impact assessment has been carried out. For successful implementation of Haloculture in the country, some capacity building measures are recommended. The education of policy makers, scientists, publicists and farmers about the potential applications and shortcomings of Haloculture is necessary. The extension and demonstration of the applicability, practicality and the socio-economic and environmental benefits of Haloculture is highly recommended.

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A STUDY ON CAPILLARY RISE IN CONTROLLED DRAINAGE SYSTEM AND ITS COMPARISON WITH UPFLOW MODEL

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Abstract

Water flowing upward through the capillary pores of the water table in unsaturated soil is defined as capillary rise and it depends on the water table depth, evapotranspiration and the soil type. Controlled drainage is an appropriate management strategy to control the water table. In the present study, the capillary rise of two soil textures was measured in a number of controlled drainage systems. The rate of capillary rise was estimated using a model. The results show that the estimation of the model is in agreement with the measured values. In loam soil at depths of less than one meter, capillary rise with a relatively gentle slope increased; however when the depth of the water table is too low, it reaches potential evapotranspiration. In depths more than one meter, the capillary rise decreased with a steep incline. In depth of more than 6 meters, the capillary rise is actually close to zero. Constant upward flow of water into the soil surface is in balance with evaporation demand; therefore, it can be used to estimate the amount of irrigation water from shallow water tables.

KEY WORDS: Controlled drainage, Capillary rise, Upflow.

Introduction

The water flow from water level through the capillary rise into the plant root zone is called upward flow. The amount of flow to the water depends on the table depth, evapotranspiration and soil type Meyer and Green (1980) showed that wheat in loamy soil obtain 28% to 36% their water requirements from a depth of one meterthus their water needs are provided from the uptake of the groundwater.

Ayars and McWhorter (1985) concluded that when designing the drain, for a shallow aquifer almost 60% of the volume of leachate should be reduced.

Greenwood et al.(1985) in a research carried out in Australia showed that water abstraction as a result of water transpiration by trees in areas with a shallow water table at 8-5 meters below ground

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level (from 2300 to 1200 mm per year) is 3 to 6 times higher than average transpiration is pasture plants.
Kahlown and Ashraf (1998) found a linear relationship between yield and water table depth and described the optimum depth to abstract from the water table is less than 22.5 cm, however, if the water table depth reaches 2-1 meters then 5-30 cm of water is required.
By comparing water tables at depths of 50 and 75 cm with free drainage in underground water depths of one meter, the impact of water level's management on corn yield and soybeans (Mejia et al, 2000) were considered. The results showed that corn and soybean at water levels of 50 cm, have a yield increase of 13.8 % and 58 % and in water levels of 75 cm, have a yield increase of 8.2 % and 12.9 % in comparison with free drainage.
De laat (1980, 1995) assumed a steady stream from a shallow water level to the surface soil, and by rewriting Darcy's equation presented the upflows model used in this study.
Shao et al (2014) studied the water use, growth and yield effects of controlled irrigation and drainage (CID) of paddy rice.
Bonaiti and Borin (2016) research recommend that controlled drainage and sub irrigation can be best applied at farm scale in northeast Italy, which will provide benefits for water conservation.

Materials and methods

A. Controlled Drainage

Water control structures, such as a flashboard riser, were installed in the drainage outlet, allowing the water in the drainage outlet to be raised or lowered as needed. This water management practice has become known as controlled drainage. When the flashboards are lowered or removed, subsurface drainage occurs more quickly. When flashboards are added to the riser, the subsurface drainage rate decreases and the height of the water level in the ditches and surrounding fields rises. Managing field water through the use of controlled drainage allows for a more timely drainage; whatsmore it also maximizes the storage of water within the field for utilization by the crop.
The transport of nitrogen from drained fields can be minimized by managing the drainage system in as such that only the minimum drainage water necessary is allowed to exit the field.
In this study, a controlled drainage system in the form of a physical model which is relatively similar to the real conditions of the farm in terms of crop pattern, soil structure , drainage system and water table was created (Figure1).
This research was carried out at a research station located in the faculty of Agriculture and Water Research Tehran University, and affiliated by the Department of Irrigation and Reclamation. In the controlled drainage treatment method, the water level control is done through the application of the outputs valve. In addition to the irrigation water that the plant uses, there is the possibility of using underground water too. The amount of water was measured between the two irrigation periods and before and after each watering period water level readings were taken

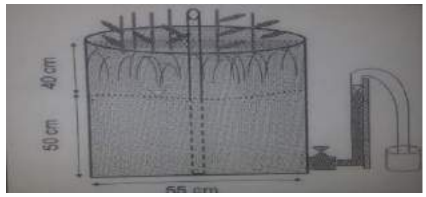

Figure1. Schematic layout of controlled drainage model

B. The Upflow model

The Upflow model estimates the amount of water that will move from a shallow water table to the topsoil for the specified environmental conditions under a steady state condition. The steady state condition assumes that the flow does not change with time.

The steady upward flow to the topsoil is estimated by means of a calculation procedure presented by De Laat (1980; 1995).

By assuming a constant flux from a shallow water table to the top soil, De Laat rewrote and integrated the Darcy equation as:

$$z = -\int_{0}^{h} \frac{k(h)}{q + k(h)} dh \qquad (1)$$

Where z [m] is the vertical co-ordinate, q the constant upward flux [m3.m-day-1] of water, h the soil matric potential per unit weight of water (head) [m], and K (h) the hydraulic conductivity [m.day-1].

Input

The input for the UPFLOW model consisted of the specifying of the the environmental conditions that are valid during the period of the upward flow.

Output

For the given environmental conditions, UPFLOW displays.

-The Expected steady upward flow from the water table to the topsoil (if any).

-The Soil water content expected in the topsoil when no water flow occurs. This is referred to as field capacity in equilibrium with the water table.

-The Amount of salt transported upward during the given period, when the water table contains salts.

-The Degree of water logging in the root zone (if any).

-The Graphical display of the soil water profile above the water table.

Results and discussion

The measured fluctuations of the level of controlled drainage water taken during the study are presented in Figure 2.

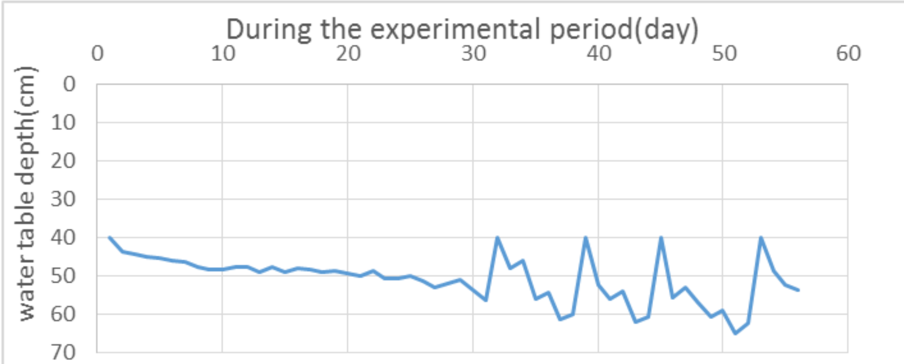

Figure 2. Fluctuation of water table for controlled drainage treatments during the experimental period.

Table 1. Amounts of water consumptive during the period (mm) through the capillary rise in a controlled drainage treatments.

treatments	WT0	WT1	WT2	WT3	WT4	total	average
CD - 1	168	7.51	30.61	54.41	65.26	153.79	38..45
CD - 2	168	69.96	38.86	38.86	33.91	173.59	34.40
CD - 3	168	58.66	30.61	38.86	28.96	157.09	93.27
						484.47	40.47

In this table, WT0 is the amount of water which was injected into the system initially applied to stabilize the water table at a depth of 40 cm, the other WT were applied to offset the declining water table due to the amount of water depleated by plant abstraction

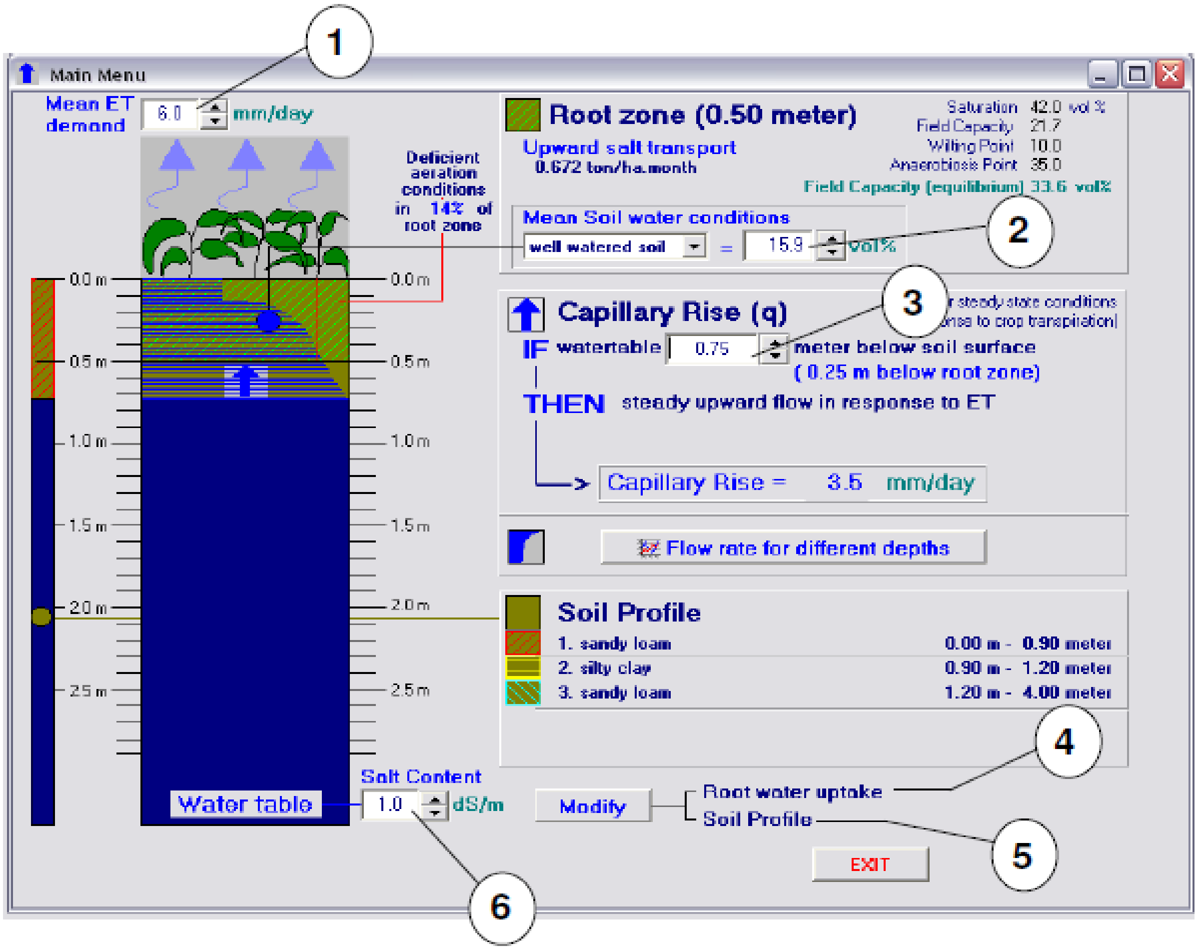

Figure 3. An example of a window model with its output

The Amount of capillary rise of the water level in the drainage control for measuring the depth of water over the soil surface and in millimeters on day two silt loam and loam soils is as per the figures provided below. Moreover, The capillary rise to the soil is estimated by the model shown in Fig 4..

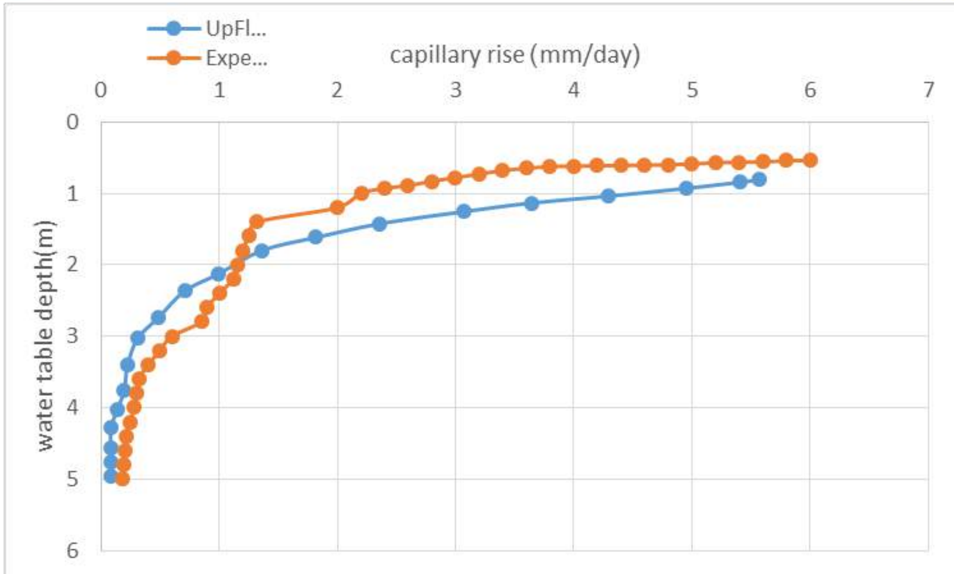

Figure 4. Capillary rise against water table in loam soil

Conclusion

Measurements show that the surface of the water table is almost constant during the experiment and small variations related to the drop in the water table before irrigation and the operation of the controlled drainage in this case is possible. The Measured results of the first series of drainage controlled trials show that approximately a third (28.2%) of the crop water requirement is provided through capillary creep, however in the second test the amount of creep increased. (38.82%). Perhaps one reason for such a rise in the amount of creep is due to the fine-textured soil of the second series as compared to the previous series. The model also showed a good estimate for both series of experiments in the investigation of the double curve (measurement and model) which shows that the model is similar to the measured values. In loamy soil and in depths of less than one meter, capillary rises with a gradient of a relatively mild increase in the depth of the water table is too low to reach potential evapotranspiration. At a depth of more than a meter with a steep climb this amount decreases and in more than 6 meters depth, the capillary rise is close to zero. The measured values are consistent with the values estimated by the model and therefore, can be used to estimate the amount of irrigation water from a shallow water table (drainage water).

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INVERSION OF PEAT SOIL: AN ALTERNATIVE DRAINAGE METHOD?

Synnøve Rivedal[1,*], Samson Øpstad[2], Sissel Hansen[3], Trond Børresen[4], Sverre Heggset[5], Torbjørn Haukås[6], Peter Dörsch[7], Johannes Deelstra[8]

Abstract

Many grasslands in Western Norway are situated on former bogs, posing agronomic and environmental challenges for crop production. Histosols with an intermediate (Hemist) or high (Saprist) degree of humification are challenging to drains, especially in areas with high precipitation in the boreal climatic zone. In peat soils the infiltration of water is low whereas waterholding capacity is high. Slow drying and loose physical structures make peat soils easily compacted by tractor traffic. Peat soils are traditionally tile-drained, but due to the aforementioned conditions, the efficiency of the drainage system is often reduced significantly shortly after operations.

In some regions of Norway, tile-drained peat soils are situated on top of a self-draining mineral soil covered by a thin layer of impermeable mineral soil. In such situations, peat inversion can be an alternative to a better drainage method. Inversion means that peat soil is covered with the underlying mineral soil while maintaining connectivity to the self-draining subsoil by means of tilted mineral soil layers. The objective of the present study was to investigate the effect of peat inversion relative to tile-drained peat on grassland yield, soil physical properties, greenhouse gas (GHG) emission and profitability.

Preliminary results from a field experiment in Norway suggest that the inversion of previously tile drained peat increases grassland yield. Mean dry matter yield for the years 2014-2016 was 9.3 and 10.95 t ha^{-1} on inverted and tile-drained peat, respectively. Top-soil physical properties of the inverted peat differ fundamentally from those in tile-drained peat and resembled mineral soil; moreover, inversion also lowered the water table.

GHG emissions during the growing seasons were less in inverted than in tile-drained peat. In 2015, this was due to a very large emission of methane (CH_4) from the tile-drained peat (4050 kg CO_2

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eq.ha^{-1}). In 2016 both CH4 and nitrous oxide (N_2O) emissions were much less in inverted than in tile-drained peat. Cumulative emissions in 2016 were -60 kg CO_2 eq. ha^{-1} CH_4 and 3000 kg CO_2 eq. ha^{-1} N_2O from inverted and 1500 kg CO_2 eq. ha^{-1} CH_4 and 9000 kg CO_2 eq. ha^{-1} N_2O from tile-drained peat. The large variation between the years could be attributed to weather conditions. In summary, the data from our field experiment suggests that the inversion of previously tile drained peat in boreal climates can lower the water table, improve soil physical properties, increase grassland yield and reduce CH_4 and N_2O emissions.

KEY WORDS: Grass yield, Soil physical properties, GHG emissions.

Introduction

Cultivation of peatlands traditionally relies on ditching and tile drainage. Histosols with an intermediate or high degree of humification are challenging to drain, especially in areas with high precipitation (Hovde & Myhr 1980). The water holding capacity of peat is high and infiltration of water is slow. High water tables in spring and the loose physical structure of peat limit its trafficability and easily lead to soil compaction (Myhr & Njøs 1983, Øpstad 1991). As a consequence, the effect of tile drainage systems is reduced at an earlier stage after establishment in peat soils than in mineral soils (Hovde 1986, Bakken 2012, Øpstad 2012).

In some regions of Norway, peat soils are situated on top of self-draining mineral soils covered by a thin layer of impermeable mineral soil. In such situations, inversion can be an alternative drainage method, especially for maintaining previously tile-drained peat soils. Inversion means that peat soil is covered with the underlying mineral soil while maintaining connectivity to the self-draining subsoil through tilted mineral soil layers (Fig. 1). The method is appropriate when the layer of peat is not too deep (<1.5 m) and has been used in Norway since 1970 (Solberg 1980, Hovde 1986 & 2001, Aandahl 2001).

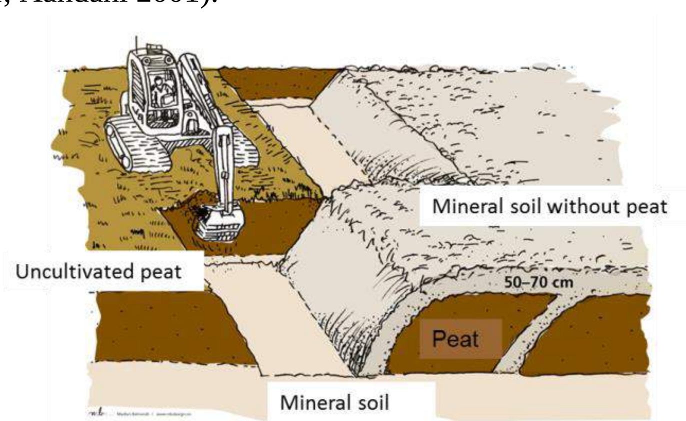

Figure 1. Principle for peat inversion.

It is likely that the inversion method has a potential to reduce the decomposition of peat, as it maintains high water tables in the peat body and protects the peat from drought and erosion. At the same time, it raises the cultivatable zone above the water table. Cultivation and fertilization of the initially nutrient-poor mineral top layer will build up soil organic matter from plant and root residues, while providing a habitat for methane oxidizing bacteria which scavenge CH_4 produced in the buried peat. Together, this will result in net C sequestration in the top layer until an equilibrium is reached (Six et al. 1998).

Preliminary measurements of GHG fluxes from inverted peat soil in Norway showed reduced emissions of CO_2 compared to tile drained peat as long as the peat was not mixed into the overlaying mineral soil (Grønlund et al., 2013). N_2O emissions were generally small and seemed to be independent of the drainage method. CH_4 emission was only detected at one of the tile-drained locations.

The objective of the present study was to investigate the effect of peat inversion relative to tile-drained peat on grassland yield, soil physical properties, greenhouse gas (GHG) emission and profitability.

Materials and methods

Site description

The experimental site is located at Fræna (62°96'N, 7°14'E) in Western Norway. The study was conducted during 2014-2016 (Figure 2).

Figure 2. Location of field site

The climate is cool and humid with an annual precipitation of 2257 mm (1961-1990) and a mean annual temperature of 6.2°C (1960-1979). Precipitation at the site varied between years and was smaller in the year of establishment(2014) than in 2015 and 2016. 2015 was wetter than normal, particularly in June (229 mm). Spring and early summer of 2016 were dry with 52 mm in May and 48 mm in June, whereas August was wet (300 mm) (Tab.1).

Table 1. Monthly precipitation (mm) during the experimental period and normal precipitation (1961-1990) at the site Fræna.

Year	Jan.	Febr.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
2014	16	41	164	125	87	127	69	230	202	254	75	336	1726
2015	221	199	232	189	114	229	137	91	163	194	291	346	2406
2016	197	227	131	148	52	48	116	300	204	170	130		1720*
1961-1990	199	165	179	142	98	109	144	153	290	289	227	262	2257

*01.01-25.11

Peatlands in the study area are ombrotrophic and dominated by nutrient poor bryophytes such as Spaghnum mosses. Some decades ago, the peatland was tile drained for grassland production. During 2012 and 2013, half of the previously tile-drained peat was inverted as explained above (Figure 1 and 3).

Figure 3. Inverted (blue) and tile drained (red) peat at the field site. Photograph taken right after inversion.

Right after inversion, the mineral soil above the peat in the inversion treatment had a heterogeneous texture and a low content of organic matter (Table 2), whereas the tile-drained peat still was defined as organic soil.

Table 2. Soil classes and different soil parameters of two samples from the mineral soil cover above the peat body of the inverted peat at Fræna.

Sample	Soil class	Clay %	Organic matter %	pH	P-AL mg/100 g	K-AL mg/100 g	K-HNO3 mg/100 g	CA-AL mg/100 g	Mg-AL mg/100 g
1	Loam	10-25	<0.1	6.1	8	10	230	47	5
2	Medium sand	<5	2.3	5.0	3	3	120	7	2

Experimental set up

In 2014, leys were established on the inverted peat and the neighboring tile-drained peat. The latter field represents the conditions typical for grassland cultivation before the inversion. N fertilizer was applied as 30 Mg cattle slurry (54 kg NH_4-N ha^{-1}) and 150 kg NH_4NO_3-N ha^{-1} in 2014. In the 2nd and 3rd ley year (2015 and 2016) only mineral fertilizer was used (260 kg N ha^{-1}), which was applied at spring (150 kg N ha^{-1}) and after the first harvest (110 kg N ha^{-1}). Three (spring, after 1st and 2nd harvest) wheel-by-wheel passes of a tractor (5.2 Mg) were performed in 2015 and 2016. For greenhouse gas (GHG) measurements, we used static chambers (Rochette & Bertrand 2008) deployed manually on permanently installed aluminium frames (52 cm x 52 cm x 25 cm). In inverted peat two chambers were located on the tilted layer (no peat underneath) and two on top of the buried peat, whereas the four chambers were placed randomly in tile-drained peat.

Measurements

During the autumn 2014, undisturbed soil cores (100 ml cylinders) were sampled from 5-10, 25-30 and 60-65 cm depth. In the inverted peat, three replicates were sampled at each four locations, whereas in the tile-drained peat two replicates were collected at two locations. The soil was analyzed for water retention (pF) at 20, 50, 100, 1000 and 15000 HPa suction, pore size distribution, pore volume, bulk density, air capacity (air volume at a matric potential of 100 HPa) and available water.

Dry matter yield (DMY) of ley was recorded in three replicates once in the establishing year 2014 and twice in the ley years 2015 and 2016. Energy content of herbage was estimated by near infrared analysis. To evaluate the effect of drainage on DMY, analysis of variance was applied using a General Linear Model (Minitab16).

N_2O and CH_4 fluxes were measured by closed chamber technique approximately weekly throughout the growing seasons 2014-2016. During a period of two weeks after fertilizer application, more frequent flux measurements were performed, whereas measurements were less frequent in autumn. Depth to the water table (WT) was measured at every gas sampling by tape measures in perforated vertical PVC tubes, permanently installed close to the chambers.

Results and discussion

Soil physics

Soil physical properties differed substantially between the mineral cover layer of the inverted peat and the tile-drained peat. Bulk density was larger and pore volume and available water a lot lower at the inverted than at the tile-drained peat. Air capacity did not differ a lot between the soils (Tab. 3).

Table 3. Bulk density, pore volume, air capacity and available water in three depths in a peat soil and an inverted peat soil at Fræna in 2014

	Bulk density (g/cm^3)		Pore volume (vol%)		Air capacity* (vol%)		Available water (vol%)	
Depth (cm)	Inverted peat	Tile-drained peat	Inverted Peat	Tile-drained peat	Inverted peat	Tile-drained peat	Inverted peat	Tile-drained peat
5-10	1.64	0.22	39.3	86.8	14.0	13.3	20.7	57.6
25-30	1.75	0.24	35.6	85.8	9.7	17.7	17.0	49.9
60-65	1.72	0.14	35.4	90.4	12.7	12.8	14.5	69.7

*: Air capacity = Air volume at a matric potential of 100 HPa

Water table

The water table was lower at the inverted than at the tile-drained peat during both growing seasons of 2015 and 2016. Mean of all measurements in 2015 was -103 and -65 cm for inverted and tile-drained respectively, whereas in 2016 it was -119 and -91 cm (Fig. 4).

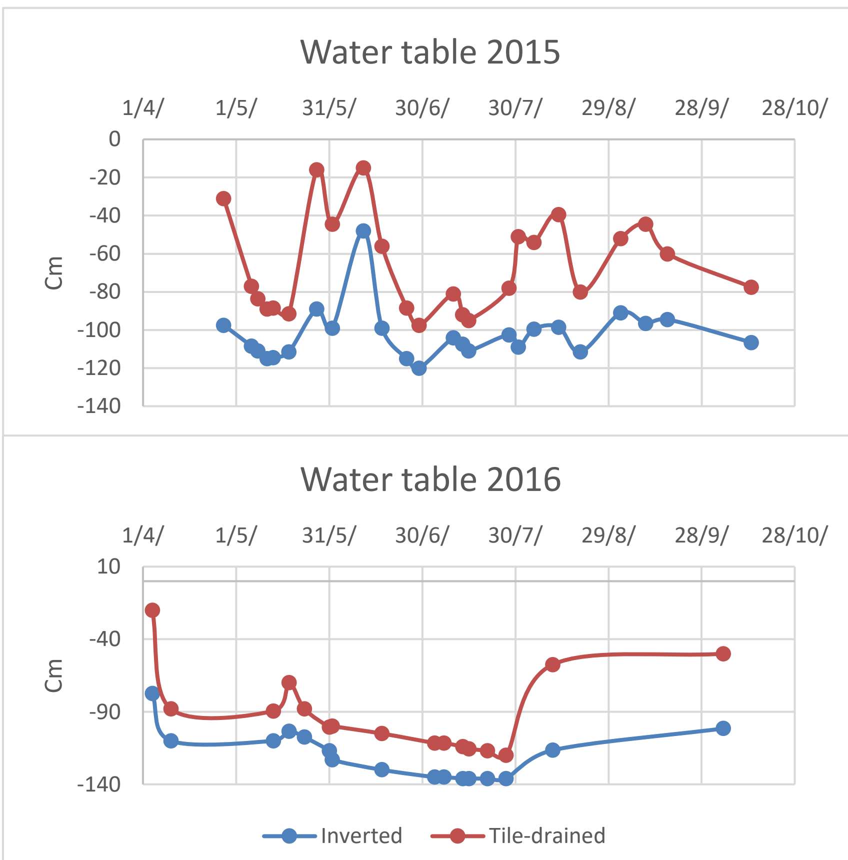

Figure 4. Depth to water table (cm) at inverted and tile-drained peat in 2015 and 2016

Grass yields

Mean DMY in the years 2014-2016 was significantly higher on inverted (10.95 t ha^{-1} yr^{-1}) than tile-drained peat (9.30 t ha^{-1} yr^{-1}). There was however a significant interaction between year and drainage method (p=0.029). Statistical analysis within each year showed that the effect of drainage method on DMY was significant only in the year 2015 (Tab. 4). It seems that inversion has the largest positive effect on yield in wet years. In dry periods, drought stress may occur due to the very low content of available water of the mineral soil cover of inverted peat (Tab. 3). Drought stress was observed in May and June 2016 when the precipitation was very low (Tab. 1). 1^{st} harvest yield tended to be lower in inverted than in tile-drained peat (results not shown), but total yield did not differ significantly between the drainage methods (Tab. 4). Yield response to peat inversion was largest for the 1^{st} harvest in 2015 with 36% higher yield compared to tile-drained peat (results not shown). In this year, the precipitation in June was more than double the normal amount, and the effect of better drainage shows.

Table 4. Effect of drainage method on DMY (t $ha^{-1}yr^{-1}$) of ley at Fræna in the years 2014-2016

Drainage method (DM)	Mean 2014-2016	2014	2015	2016
Tile-drained	9.30	4.67	11.19	12.03
Inverted	10.95	5.46	14.90	12.50
p-value				
DM	0.012	ns	0.04	ns
Year X DM	0.029			
Year	<0.01			

GHG emissions

Figure 5 shows that during the three months of gas measurement in 2014 differences in cumulative GHG emissions in inverted and tile-drained peat were small. More N_2O was emitted from the inverted (1883 kg CO_2 eq.ha^{-1}) than the tile-drained peat (1425 kg CO_2 eq.ha^{-1}), whereas CH_4 emission was lower (8 and 270 kg CO_2 eq.ha^{-1}, respectively). In 2015, measurements throughout six months showed a very large cumulative CH_4 emission from the tile-drained peat (4050 kg CO_2 eq.ha^{-1}), whereas CH4 emission from inverted peat was very low (5 kg CO_2 eq.ha^{-1}). April, May and June 2015 were very wet (Tab. 1), exceeding the drainage capacity of the tile-drained, thus causing anoxia by high water table and large CH_4 emissions. N_2O emission did not differ between the two drainage methods in this year, being 3365 and 3953 kg CO_2 eq.ha^{-1} for inverted and tile-drained peat respectively. The total cumulative GHG emission during the six months of measurements in 2016 was larger for tile-drained than inverted peat (Fig. 4). Even though the precipitation in May and June 2016 was very low, it was very wet after fertilization. This caused a very high emission of N_2O from the tile-drained peat (8973 kg CO_2 eq.ha^{-1}) whereas it did not affect N2O emission from inverted peat (3020 kg CO_2 eq.ha^{-1}) which was lower than in the year before. Inverted peat showed net-uptake of CH_4 (-63 kg CO_2 eq.ha^{-1}) whereas tile-drained peat showed net-emission of CH_4 (1533 kg CO_2 eq.ha^{-1}). A smaller CH_4 emission in 2016 than 2015 from the tile-drained peat may be due to less precipitation.

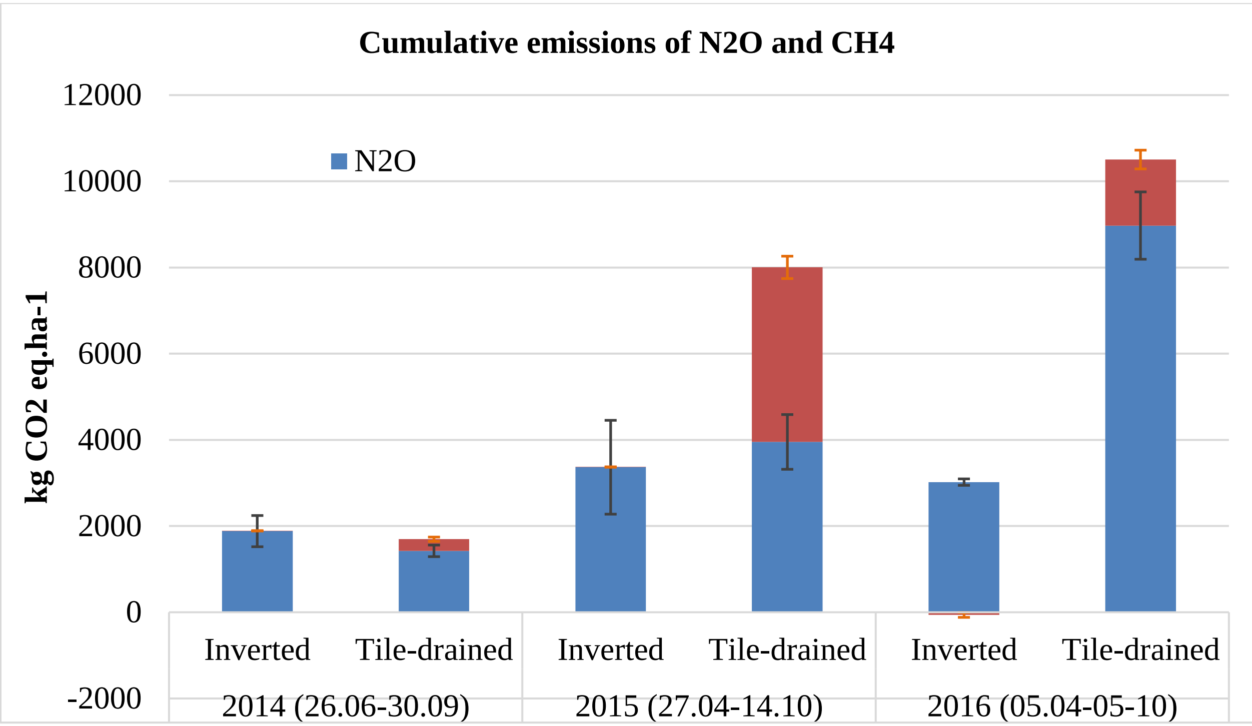

Figure 5. Cumulative emissions of N_2O and CH_4 from inverted and tile-drained peat during 26.06-30.09 2014, 27.04-14.10 2015 and 05.04-15.10 2016 calculated as CO_2 equivalents per ha and period. Bars represent means of four replicates, black and yellow lines represent standard deviation (n=4) of N_2O and CH_4 emissions, respectively.

Conclusion

The conclusion from our study so far is that inversion of previously tile drained peat lowers the water table, improves soil physical properties, increases grassland yield and reduces methane and nitrous oxide emissions.

Acknowledgement

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BIODRAINAGE: AN ALTERNATE DRAINAGE SYSTEM TO MANAGE WATERLOGGING AND SALINITY

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Abstract

In the absence of the provision of adequate drainage, waterlogging and associated soil salinity become major impediments to the sustainability of irrigated agriculture. Though, conventional engineering drainage technologies such as subsurface or vertical drainage are able to combat the problem, yet these methods are costly and generate huge quantities of drainage effluent which result into disposal problems. These conventional options are quite successful where large tracts of land are affected by waterlogging and a continuous salinity exists Biodrainage, which removes the excess soil water via deep rooted fast growing trees through evapotranspiration using bio-energy is proposed as an alternate to the abovementioned engineering approaches. Irrigation of high transpiring forest species has also been put forward for reuse of wastewater and the conservation of nutrient energy into biomass and thereby bringing multiple benefits such as fuelwood production, carbon sequestration, environmental sanitation and eco-restoration. Biodrainage potential of perennial vegetation in general and trees in particular is a cardinal component for designing and implementing biodrainage projects. Consumptive water use of plants varies with the age, geometry, soil properties, water table, salinity and climatic conditions. This varies between 6500 to 28000 m3 ha-1 year-1 and under ideal conditions, a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years. Trees of the genes such as *Eucalyptus, Populus, Casuarina, Dalbergia, Syzigium*, *Acacia, Prosopis, Leucaena* etc. are reported as being effective to lowering a shallow water table and reverse salinity trends. Amongst different trees studied at different places, Eucalyptus was preferred because it grows fast in a wide range of conditions, grows straight thus creating a low shading effect on associated crops, and has luxurious water consumption in excess soil moisture conditions. Small and marginal farmers may not be able to set part of their farm aside for bio drainage activities therefore biodrainage technology may be more suitable on large farms or public lands. However, integration of trees such as *Eucalyptus* and *Populus* along with crops in a unified agroforestry system or on approach roads or field bunds or on dykes of ponds in an integrated farming system will be a viable preposition. For effective understanding and implementation, several case studies on the role of biodrainage for managing waterlogging and salinity are discussed in this paper.

KEY WORDS: Salinity, Water logging, Eucalyptus, Irrigated agriculture, Biodrainage, Case Studies.

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Introduction

Introduction of canal irrigation without adequate provision for drainage in arid and semi-arid regions results in water table rise leading to waterlogging and secondary salinization in large areas in irrigation commands. These problems are the result of a multitude of factors, including seepage from unlined canals, inadequate provision of surface and subsurface drainage, over irrigation and use of poor quality groundwater for irrigation. Globally about 10% of the land area is affected by waterlogging (Setter and Waters, 2003) and over 6% by salinity (FAO, 2008). In India, about 6.7 million ha of land is affected by different levels and types of salinity, out of which nearly half are under irrigated agriculture (ICAR, 2010). Severely waterlogged saline soils occur in about two million ha area in arid/ semi- arid north western states of Punjab, Haryana, Rajasthan and Gujarat and one million ha each in the coastal and black cotton Vertisol regions of India. It is projected that about 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025. Use of saline/ alkali groundwater and climate change will further accentuate the threats (CBIP, 2015). Waterlogged saline soils apart from environmental degradation result in poor crop yields by reducing crop yields by as much as 80% (Shabala, 2011) and finally in abandoning the land from cultivation. In India, yearly crop loss due to waterlogging has been estimated to be more than 2 m tons (ICRISAT, 2009). The economic loss was estimated to be about Rs. 23,900/ha with a total annual loss of Rs. 1669 million (about US$ 37 million) from the waterlogged saline area of Haryana, India (Datta and Jong, 2002). The crop yields and relative yield loss caused due to waterlogging and soil salinity of major crops are presented in Table 1 (Joshi, 1994). Thus, twin menaces of waterlogging and salinization represent serious threats to the sustainability of irrigated agriculture and calls for appropriate reclamation measures.

For favourable plant growth, optimum balance of water, air and salt in the root zone is a primary requirement which can be achieved by providing adequate drainage. No doubt, the conventional technologies such as surface, subsurface or vertical drainage overcome the problem of waterlogging and salinity, but they have limitations like high cost of construction and subsequent maintenance cost and safe disposal of drainage effluent during reclamation and afterwards. Disposal of drainage effluent which contains nutrients, salts, agro-chemicals and other pollutants in water bodies had resulted in pollution of many river basins like the Indus basin in Pakistan, the Murray-Darling Basin Catchment in Australia, San Joaquin Valley in USA and various river systems in India. To combat drainage problem of such an extent, the technology needed to be less expensive, location specific, sustainable and environment friendly for its large scale adoption by the farmers.

Biodrainage could be a viable option. It is a combined drainage-cum-disposal system. Biodrainage can be defined as "pumping of excess soil water by deep-rooted vegetations through evapotranspiration using their bio-energy". Reliance on capability of vegetation to reduce water table has been reported promising both in India as well as in other countries. The main physiological feature of such vegetation is profuse transpiration whenever the root system comes in contact with groundwater. The biodrainage technique is eco-friendly as the biodrainage plantations purify the environment by absorbing greenhouse gases and releasing oxygen into the environment, environmentally safe as it does not generate any drainage effluent to dispose, economically attractive because it requires only an initial investment for planting the vegetation, and when established, the system could produce economic returns by means of fodder, wood or fiber harvested and has an additional advantage in term of carbon locked in the timber. The first documented use of the term biodrainage can be attributed to Gafni (1994). Prior to that date Heuperman (1992) used the term bio pumping to describe the use of trees for water table control.

Table 1. Losses due to water logging and soil salinity

Crop	Normal lands	Salt affected lands	Waterlogged lands
Paddy	39.9	21.8 (45)	23.0 (42)
Wheat	26.0	15.8 (40)	18.6 (38)
Cotton	16.3	6.1 (63)	3.7 (77)
Sugarcane	636.8	330.2 (48)	247.5 (61)

Waterlogging and Soil Salinity

A soil is said to be water logged when the ground water table gets linked to soil water in the crop root zone and remains like this for the remaining period in a year (Michael and Ojha, 2006). It results restriction of the normal circulation of the air, decline in the level of oxygen and increase in the level of carbon dioxide. The critical depth depends on the kind of crop, but waterlogging is commonly defined as light for a soil profile depth of 3 m for substantial parts of the year, and moderate for less than 1.5 m. The severe degree occurs with a water table at 0-30 cm depth, and also included is ponding, where it rises above the surface (FAO, 1994). As an illustration, rise in water table at different places in Haryana (north India) between 1974 and 2004 is shown in Figure 1.

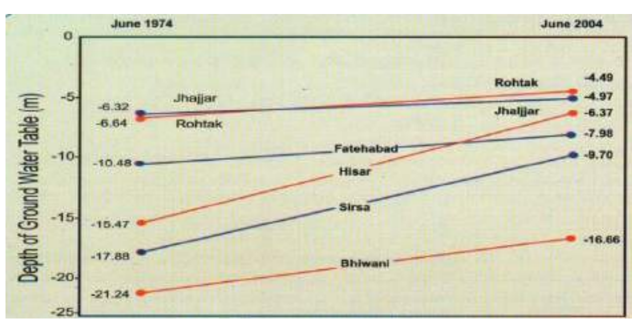

Figure 1 - Trend in rise in water table in Haryana. Source: Jeet Ram et al., 2008

Soil salinity is another problem in arid and semi-arid regions. It refers to presence of excess amount of soluble salts in soil water creating its high osmotic pressure which restricts crop water uptake and ultimately resulting in poor plant growth. Salinity occurs when salts are transported to surface by rising water and got concentrated with evaporation. Several species of trees and crops can be grown in alkali, saline and saline water logged soils. Relative tolerance of crops and trees to salt stress is reported in Tables 2 and 3.

Table 2: Relative tolerance of crops and grasses to soil ESP. Source: CSSRI, Karnal, 2007

Tolerant **ESP, 35-50**	**Moderately tolerant** **ESP, 15-35**	**Sensitive** **ESP <15**
Karnal grass *(Leptochloa fusca)*	Wheat *(Triticum aestivum)*	Gram *(Cicer arietinum)*
Rhodes grass *(Chloris gayana)*	Barley *(Hordeum vulgare)*	Mash *(Phaseolus mungo)*
Para grass *(Brachiaria mutica)*	Oat *(Avena sativa)*	Chickpea *(Cicer arietinum)*
Bermuda grass *(Cynodon dactylon)*	Shaftal*(Trifolium resupinatum)*	Lentil *(Lens esculenta)*
Rice *(Oryza sativa)*	Lucerne *(Medicago sativa)*	Soybean *(Glycine max)*
Dhaincha*(Seshania aculeate)*	Turnip *(Brassica rapa)*	Groundnut *(Arachis hypogea)*
Sugarbeet*(Beta vulgaris)*	Sunflower *(Helianthus annus)*	Sesamum*(Sesamum oriental)*
Teosinte*(Euchlaena maxicana)*	Safflower *(Carthamus tinctorius)*	Mung*(Phaseolus aureus)*
	Berseem*(Trifolium alexandrinum)*	Pea *(Pisum sativum)*
	Linseed *(Linum usitatissimum)*	Cowpea *(Vigna unguiculata)*
	Onion *(Allium cepa)*	Maize *(Zea mays)*
	Garlic *(Allium sativum)*	Cotton *(Gossypium hirsutum)*
	Pearl millet *(Pennisetum typhoides)*	

Table 3: Relative tolerance of tree species to soil alkalinity. Source: Singh et al., 1993

Average pH2 (0-120 cm)	Fuel-wood/Timber species	Fruit trees
More than 10.0	*Prosopis juliflora* (Paharikiker) *Acacia nilotica* (Kikar) *Casuarina equisetifolia* (Australian pine)	*Achras japota* (Chikoo)
9.0 to 10.0	*Tamarix articulate* (Frans) *Terminalia arjuna* (Arjun) *Eucalyptus tereticornis* (Safeda) *Albizzia lebbek* (Papri) *Pongamiapinnata* (SirisKaranj) *Sesbaniasesban (*Dhaincha) *Emblicaofficinalis (Amla)*	*Zizyphus maurtiana* (Ber) *Carissa carandus* (Karaunda) *Psidium guajava* (Amrood) *Syzygium cumini* (Jamun) *Phoenix dectylifera* (Khajoor) *Aegle marmelos* (Bael)
8.2 to 9.0	*Dalbergia sisoo* (Shisham) *Morus alba (Sehtoot)* *Grevilla robusta* (Silver Oak) *Azadirachta indica* (Neem) *Tectona grandis* (Teak) *Populus deltoids* (Poplar)	*Punica granatum* (Anar) *Prunus persica* (Aru) *Pyrus communis* (Nashpati) *Vitis vinifera* (Angoor) *Mangifera Indica* (Aam)

Mechanism of Biodrainage

The root systems of trees intercept saturated zone or unsaturated capillary fringe above water table and control shallow water table. The primary objective of a bio-drainage system is to lower a shallow groundwater table to below the ‘‘critical depth’’ (2 m below ground surface is generally accepted as a safe depth) of the capillarity-induced evaporative processes that cause salinization (Heuperman et al. 2002; Kapoor 2001). For efficient biodrainage system, trees should be fast growing having high rate transpiration system so that they absorb sufficient quantity of water from the capillary fringe located above the ground water table. The roots of herbaceous annuals have little or no contact with water table. The absorbed water is translocated to different parts of plants and finally more than 98% of the absorbed water is transpired into the atmosphere mainly through the stomata. Under ideal conditions, a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years (Gafni and Zohar, 2001; Heuperman et al., 2002; Kapoor, 2001). This combined process of absorption, translocation and transpiration of excess ground water into the atmosphere by the deep rooted vegetation conceptualizes biodrainage.

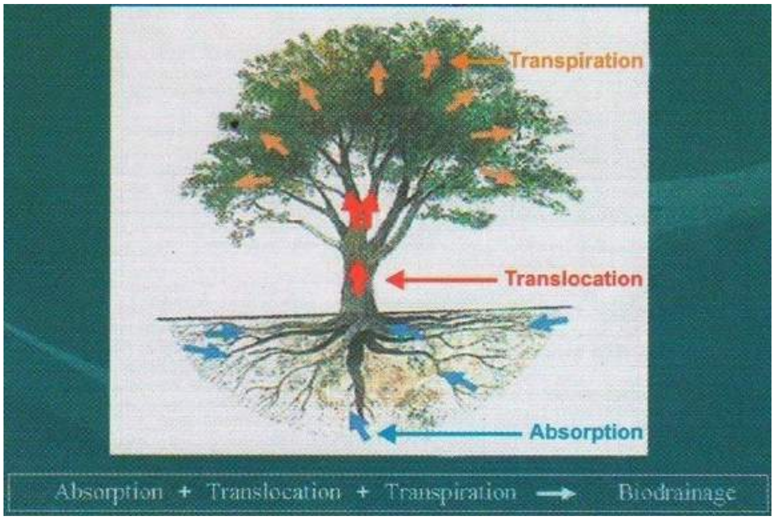

Figure 2 - Concept of biodrainage

Situations Suitable for Biodrainage Application

Depending upon land use, biodrainage mechanism can be applied both in dry land/rainfed and irrigated agriculture. In rainfed systems, bio-draining ability of vegetation can be utilized mainly for recharge control, interception of ground water flow and discharge enhancement.

Extensive clearing of area for agricultural development and cultivation of annual crops with shallow rooting crops may result in higher recharge and ultimately rise in water table and causing waterlogging and salinity as was observed in Kyabram, Australia. Re-vegetation of recharge areas by deep rooted tree plantation minimizes deep seepage losses in the higher parts of the landscape to minimize discharge problems referring recharge control and reduction of localized salinity and discharge problems in lower part of the landscape. Excessive evaporative demand of newly planted vegetation may lead to dry landscape causing reduced river flow, drying of well and increase in groundwater salinity. The interception of groundwater flowing through permeable layers overlying low permeability strata reduce discharge problems further down the slope. In dry land areas, extensive clearing upsets the hydrological balance, resulting in saline discharge in low lying land areas, which affects agricultural productivity and water quality in stream systems. Reclamation techniques for dry land salinity in waterlogged discharge areas focus on the restoration of the hydrological balance by planting biodrainage vegetation using the concept enhanced evapotranspiration (Heuperman, 2000).

In irrigated areas biodrainage can be useful for control of rise in water table, intercepting seepage water from channels and management of salinity as in convention drainage system as discussed below.

a. ***Water table control:*** Shallow water table causes root zone soil salinization which adversely affects crop growth. Biodrainage in irrigation areas lowers water tables below the critical depth, which is defined as the depth at which capillary salinization is negligible.

b. ***Channel seepage interception:*** Channel seepage can be a major contributor to water table rise and consequently can cause water logging and salinity problems in the adjoining land. Water quality of seepage water is normally good which if intercepted can be productively used by crops. In cases if seepage water is not intercepted and left to evaporate it will increase salinity.

c. ***Biodrainage cum conventional drainage systems:*** For the optimum growth of biodrainage crops also, salt accumulation in the root zone should not exceed the threshold level. Where biodrainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

Planning & Design for Biodrainage Plantation

The primary requirement for planning and deciding the location for putting drainage plantings is the catchment water balance and precise identification of recharge and discharge areas in the landscape. The following issues should be considered in the development of biodrainage systems:

● Water balance: In irrigated areas due to net incremental recharge ground water table starts rising causing water logging. To overcome the above problem, the objective of any drainage scheme, is to achieve water balance before the ground water table rises up to the critical depth, which in general may be taken as 2.0 m below ground level. Plantations of deep rooted trees with high rates of transpiration should extract ground water equal or more than the net recharge so that water table is kept below the critical depth root zone. Tree plantations often use water at higher rates because of the high aerodynamic roughness which may be even more pronounced because of the so-called clothesline effect prevailing in rows of trees, substituting for a conventional drain pipe.

● Area under plantation for water balance: For sustainable water balance, the area to be covered under biodrainage vegetation should be the minimum but large enough so that amount water removed through evapotranspiration should equal the total annual recharge.

● Salt tolerance: Salt tolerance will be an important criterion for (potentially) saline discharge environments, water use considerations will prevail in recharge control situations where salinity is of no concern and in channel seepage scenarios with low-salinity water supply. Water use capacity of trees decreases with increase in water salinity. Therefore, biodrainage crops need to be salt tolerant.

● Drawdown of water table: Crops, including trees, act as bio pumps; they depress the water table directly underneath plantation areas and consequently lower the water table in the surrounding area. Draw down effect depends on water use capacity of trees, rate of recharge in surrounding area, soil hydraulic conductivity, depth of deeper barrier layers, root system of trees and salt-tolerance of tree species.

● Salt balance: Salt balance determines the sustainability of plant water use and lowering of water table. If the salts moving into the root zone are not either (i) taken up by the vegetation and harvested or (ii) removed from the root zone by leaching, the vegetation will succumb to salinity. Large volumes of irrigation water even of low salinity significantly increase salt imports. Salinity buildup beyond a threshold level will certainly hamper plant growth. To achieve the salt level below the critical level, drainage of these salts below the crop root zone is considered a necessity for optimum plant growth. The Israeli experience has shown that the bio-drainage technique can effectively lower a shallow water table and reverse salinity trends, provided that the overall water balance is negative, i.e. that the water inputs match the water use by the tree plantation and local drainage characteristics (Gafni and Zohar, 2007). In absence of conventional drainage, the irrigated crops and biodrainage vegetation should be salt accumulating so that salts introduced by irrigation can be removed through crop harvest. But the ability of the biodrainage system to maintain a salt-balance is not clear. The salt uptake by plants in general is negligible compared to the total salt applied in irrigation supplies as trees do not bio-harvest as the roots exclude salts during water uptake making a saltwater lens below the root zone (Chhabra and Thakur, 1998; Heuperman, 1999). Chhabra and Thakur (1998) reported that 3 year old Eucalypts *(Eucalyptus tereticornis)* and 4 year old bamboo *(Bambusaarundinacea)* having low groundwater salinity 0.4 dS/m and water table depth 1.5 m had very high biodrainage value (plant water use) up to 5.5 m and 4.2 m per year, respectively. Biodrainage values were lower at the higher groundwater salinities. In high-salinity environments plant salt uptake might be negligible in relation to the salts present in the system, under low-salinity scenarios salt balance by plant uptake and removal might be achievable (Heupermanet et al., 2002). On dry weight basis, mineral content in leafy vegetables is reported 14 % followed by other vegetables (8%), roots and tubers (6.5%) pulses and legumes (3.5%) and cereal grains (2%) (ICMR, 1989). Maximum soil water salinity which can be controlled by bio-drainage is around 3 dS m^{-1} in medium run (Akram et al., 2008). In cases where bio drainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

● Economic aspects: Biodrainage plantations should be of high economic value so that costs associated with planting and maintenance can be covered from the sale of the tree produce. In direct benefits of planting trees on farm lands in terms of organic carbon build-up, carbon sequestration in biomass and other eco-system services should also be considered.

Suitable Plant Species for Biodrainage

The vegetations with profuse transpiration ability appear to be a promising tool for improvement of drainage situation through removal of excess water. Consumptive water use of plants varies with the age, geometry and soil water and salinity and climatic conditions. The rate of fall of the water table doubled with the development of the trees (Rodríguez-suárez et al., 2011). It has been demonstrated that under ideal conditions, consumptive use of trees varies between 6500 to 28000 m3 ha-1 year-1 and a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years (Gafni and Zohar, 2001; Heuperman et al., 2002; Kapoor, 2001, NIH, 1999). For biodrainage, amongst different trees, Eucalyptus has been used the most for this purpose because of its luxurious water consumption (Dong et al., 1992). The roots of Eucalyptus penetrate in the soil at 2.5 meters per year and utilize ground water as well as water from upper vadose zone (Calder et al., 1997). It goes straight thus low shading effect, reduces groundwater recharge with minimal competition with adjacent crops for water and grows well under a wide range of climatic conditions (White, 2002). In waterlogged areas, it can be successfully grown by ridge planting. The world's Eucalyptus plantation area has increased to 19 million ha because of its fast growth rate, favourable wood properties and carbon sequestration and thus seems to be a good option for biodrainage (Iglesias Trabado et al., 2009). Eucalyptus species use more water than native species of trees (Zahid et al., 2010). Early studies in Australia (Greenwood et al., 1985) suggested that the rates of transpiration and groundwater uptake by Eucalyptus underlain by relatively shallow (5-8 m below surface) water tables were 3-6 higher than from pasture. In Israel, annual transpiration of three-year-old trees *E. Camaldulensis* was found to be 1,360 mm (Zohar et al., 2008). In Indian desert, plantation of *Eucalyptus camaldulensis*, *E. fastigata*, *E. rudis* and *Corymbia tessellaris* on raised bunds, improved vegetation cover with simultaneous decrease in water table. Performance of *E. rudis* was found to be the best with respect to growth, biomass, transpiration rate and overall bio-drainage potential (Bala et al., 2014). Average over a period of six years the evapotranspiration rate of Eucalyptus was reported to be 3446 mm per year. In Australia, 8 years old Eucalyptus plantation lowered the water table 2 meters or more and piezometric head by 1.5 m (NIH, 1999). In Western Australia, annual tree water use values for *Eucalyptus Camaldulensis* ranged from 0.6 A pan for irrigated Eucalyptus with full canopy cover (Marshall and Chester, 1991) to 1.9 Apan irrigated with seepage affluent (Morris and Wefner, 1987). Water use of 3-5 years old *Acacia nilotica* was found to be 1248 and 2225 mm per annum on severe and mild saline soils, respectively (NIH, 1999).

Studies conducted on abandoned waterlogged degraded land in Haryana, India to lower down water table found trees like Eucalyptus hybrid, *Eucalyptus tereticornis* C-10, *Eucalyptus tereticornis* C-130 and *Prosopis juliflora* fast biodrainers, *Eucalyptus tereticornis* C-3, *Callistemon lanceolatus* and *Melia azedarach* in the category of medium biodrainers whereas *Terminalia arjuna* and *Pongamia pinnata* slow biodrainers. An overall 20 cm decline in water table was recorded during the 5th year growth compared to control (without plantation). Leaf area was found to be a cardinal component of biodrainage potential. (Toky et al., 2011). To make use of unproductive land and lower the elevated groundwater table (GWT) suitability of 9 multipurpose trees *(Prunus armeniaca L.)*, black poplar *(Populus nigra*), black willow *(Salix nigra)*, Eastern catalpa *(Catalpa bignonioides)*, Euphrates poplar *(Populus euphratica Oliv.)*, Russian olive *(Elaeagnus angustifolia L.)*, salt cedar *(Tamarix androssowii)*, Siberian elm *(Ulmuspumila L.)*, swamp ash *(Fraxinus pennsylvanica)*, and white mulberry *(Morus alba)* for biodrainage were studied on sandy and loamy slightly saline soils on degraded agricultural landscapes in Khorezm, Uzbekistan, Aral Sea Basin. *E. angustifolia* ranked the highest, combining high water use, fast growth and production of nutritious feed. *Populus* spp. and Ulmuspumila L. ranked lower but still represented potential candidates for biodrainage purposes whereas fruit species such as *P. Armeniaca* and M. alba, though desirable from the farmer's financial viewpoint, showed low biodrainage potential. The annual stand transpiration amounted to 1830, 1470, and 730 mm for *E. angustifolia*, *U. pumila* and *P. euphratica*, respectively. Transpiration rates was highly correlated with length of fine roots whereas weakly correlated with leaf area and no correlations were found between salt content in plants and water uptake under conditions of slight-to moderate root zone soil salinity (Khamzina et al., 2006). In north-western China, *Lycium barbarum* and *Puccinellia chinamponsis* proved to be very effective in lowering shallow ground-water tables and facilitating some leaching of salts from the surface layers (Zhao et al., 2004). Other suitable species for block plantations are *Populus deltoides, Casuarina glauca, Terminalia arjuna, Pongamia pinnata* and *Syzygium cuminii* etc. Apart from the planted species, *Prosopis juliflora, Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity. The well managed multipurpose tree species on farm enhance the overall productivity, improvement in soil fertility, soil conservation and nutrient cycling, micro-climate amelioration, carbon sequestration, bio-drainage, bio-energy and bio-fuel production etc. There is consensus that biodrainage, when properly implemented, can lower the water table and solve problems associated with waterlogged areas and canal seepage (Ahmad et al., 2007).

Though problem of salinity can be managed by removal of excess groundwater through the transpiration by vegetation thus lowering down the water table below the root zone but the performance or suitability of biodrainage in saline conditions is still a debateable issue. According to Kapoor and Denecke (2001) biodrainage could be used in various regions ranging from humid to semi-arid areas, except when the ground water EC is greater than 12 dS m-1. However, Akram and Liaghat (2010) are of the view that biodrainage does have a high sensitivity to salinity in regions with arid and semi-arid climates. Biodrainage cannot be a good alternative to conventional drainage systems when the irrigation water is too saline. Due to increasing salinity over the time, evapotranspiration efficiency of the tree strips reduces to such an extent that actually will lose its applicability. Horticultural and landscape plants indicate 100% loss of relative growth or yield at 8, 16, 24 and 32 dS m-1 for sensitive, moderately sensitive, moderately tolerant and tolerant crops, respectively (Blaylock. 1994). Levels of 4 to 5 dS m-1 affect many crops and above 8 dS m-1 affect all but the very tolerant crops (Cardon et al., 2011). In the case of Eucalypt species, it reduces to about one-half of potential when the water salinity increases to about 8 dS m-1 (Oster et al. 1999). Yet there are many plant species which are tolerant to salinity and grows well.

Eucalyptus occidentalis performed better than *E. camaldulensis* under the more saline situation emphasizing selection of salt tolerant species. The annual transpiration of Eucalyptus in saline environment highlighted the ecological benefit of eucalyptus plantations in lowering the water table, even in a saline habitat, although their economic viability under such conditions remains limited (Zohar et al., 2008). Singh et al. (2013) were of the view that bio-control measures involving selection of more salt-tolerant crops, residue management, and biodrainage manages soil and water salinity for sustainable agriculture. The Central Soil Salinity Research Institute (CSSRI) at Karnal, India, presents data on the tolerance of tree species to soil salinity as shown in Table 4 (Tomar and Gupta, 1999).

Table 4: Suitability of tree spp. for saline soils

Tolerant (ECe 25-35 dS/m)*	*Tamari troupii, T. articulata, Prosopis juliflora, Pithecello biumdulce, Parkinsonia aculeata, Acacia farnesiana*
Moderately tolerant (ECe 15-25 dS/m)	*Callistemon lanceolatus, Acacia nilotica, A. pennatula, A. tortilis, Casuarina glauca, C. equisetifolia, Eucalyptus camaldulensis, Leucaena leucocephala*
Moderately sensitive (ECe 10-15 dS/m)	*Casuarina cunninghamiana, Eucalyptus tereticornis, Acacia auriculiformis, Guazum aulmifolia, Leucanea shannonii, Samanea saman, Albizzia caribea, Senna atomeria, Terminalia arjuna, Pongamia pinnata*
Sensitive (ECe 7-10 dS/m)	*Syzygium cumini, S. fruticosum, Tamarindus indica, Salix app., Acacia deanei, Albizia quachepela, Alelia herbertsmithi, Ceaselpimia eriostachya, C. velutina, Halmatoxylon brasiletto*

* ECe is the average rootzone salinity as measured in a saturation extract

Source: Tomar and Gupta, 1999

Case Studies

Biodrainage to control channel seepage in Indira Gandhi Nahar Project, Rajasthan, India

Large areas along the main canal in the Indira Gandhi Nahar Project (IGNP) became waterlogged mainly due to seepage from the canal and presence of impervious gypsum layer at shallow depth. Before IGNP, the depth of water table in the command area of Phase I generally ranged between 40 and 50 m below the surface water table and the quality of groundwater was highly saline and unfit for irrigation. With the introduction of irrigation, the groundwater table started to rise at the rate of 0.92 m year-1. In Phase II of the project, the groundwater table before the advent of irrigation generally ranged between 20 to 100 m below surface. With irrigation, it has been rising, though not at the same rate as Phase I. To protect the canal form sand drift and meet the timber, fuel and fodder need of the locals, plantations were raised in the area. The afforestation schemes included canal side plantation, block plantation, sand dune stabilization, pasture development, roadside plantation and environmental plantation. The main trees planted in irrigated areas were *Eucalyptus camaldulensis, Dalbergia sissoo* and *Acacia nilotica*, whereas *Prosopis cineraria, Tecomella undulata* and *Ziziphus* in unirrigated areas. *Lasiuruss indicus* grass was planted for pastures and in between mulch lines for stabilization of sand dunes. Along the canal, the width of plantation was 100m on the right side and 200 m on the left. Amongst different trees, growth of *Eucalyptus camaldulensis* was the fastest whereas Prosopis cineraria the slowest. The annual rate of transpiration was found to be 2971mm, about 1.2 class A pan evaporation (Heuperman et al., 2002; Kapoor and Denecke, 2001). Plantations made along the canal and around the submersed areas removed excess water through biodrainage and the groundwater table fell by about 15 m after six years. As a result of that inundation disappeared from most of the affected area. Considering the annual rate of transpiration of 3000 mm, for maintaining water balance roughly 5% of the area needs tree plantation.

Analysis of factors responsible for waterlogging and salinity in IGNP found were large percolation losses from the irrigated fields, seepage from channels, over use of water for irrigation, relatively low levels of groundwater development, subsurface barriers and absence of natural drainage. An optimal policy to control the problems of waterlogging and salinization require lower water allowance, efficient irrigation methods, conjunctive utilization of surface water and groundwater, planting trees and artificial drainage (Sharma, 2001).

Eucalyptus based agroforestry system for waterlogged soils at Puthi, Haryana, India

Two plantations 350 m apart comprising of 18 years old *Eucalyptus tereticornis* (Mysure gum) raised at a spacing of 3mx3m along the road and railway line on alluvial sandy loam soil at Dhob-Bhali, Rohtak (Haryana), lowered groundwater table by 0.91 m but no increase in salinity underneath the plantations than the ground water table underneath the adjacent fields without plantation Ram et al. (2007). The spatial extent of lowering of groundwater table in the adjacent fields was up to a distance of more than 730 m from the edge of a plantation.

But in developing countries like India, farmers have small holdings and not interested to put the land under sole forestry plantations which yield after a gap of five to six years. Under such situations, planting trees on farm boundaries in form of agro forestry can be a viable and remunerative option, which will provide regular income also. Parallel strip plantations of *Eucalyptus tereticornis* (Mysure gum) spaced at 66 m and each strip-plantation contained 2 rows of trees at a spacing of 1 m x 1 m resulting in a density of 300 plants ha-1 lowered the ground water table underneath the strip-plantations by 85 cm compared to adjacent unvegetated fields in 3 years (Ram et al., 2011). In this field study, four parallel strip-plantations of clonal *Eucalyptus tereticornis* were raised in December 2002 on four ridges constructed in north-south direction in 4.8 ha canal irrigated waterlogged fields of farmers at village Puthi, Hisar, Haryana. The shapes of draw down curves of ground water table in both transects were similar to the combined cone of depression of 4 pumping wells working simultaneously for a long period indicating that 4 strip plantations of clonal *E. tereticornis* were also working as bio-pumps. Water table was brought down mainly be due to the luxurious use of water by Eucalyptus plantation which transpired 268 mm per annum against the mean annual rainfall of 212 mm. Location of the research plot is shown as Figures 3(a), 3(b), 3(c) and 4.

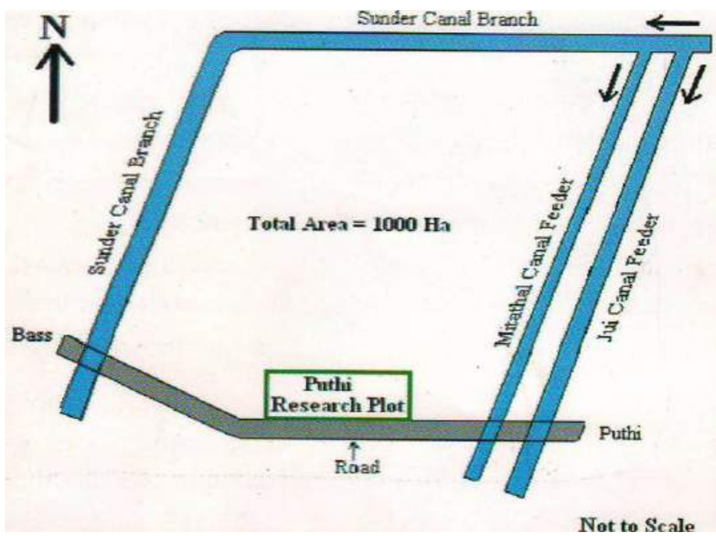

Figure 3(a) - Land locked area. Source: Jeet Ram et al., 2008

Figure 3(b) - Mithathal canal and Jui canal feeders. Source: Jeet Ram et al., 2008

Figure 3(c) - Sunder canal branch. Source: Jeet Ram et al., 2008

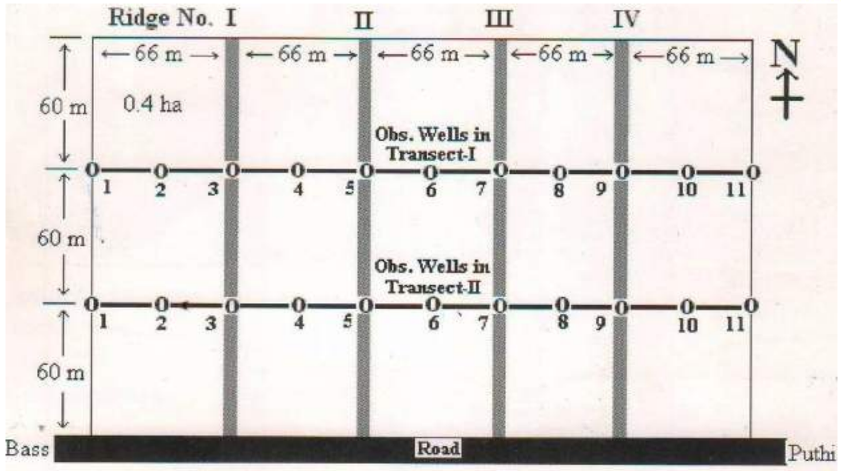

Figure 4 - Layout of experiment at Puthi showing position of observation wells and plantation strips. Source: Jeet Ram et al., 2008

Tree plantations harvested after 5 years and 4 months of growth produced 33 t ha-1 of root and shoot biomass and sequestered 15.5 t ha-1 carbon. Planting trees requires only initial investment and when established, the system provides economic returns by means of fodder, wood or fibre harvested. In this study, benefit-cost ratio was 3.5:1 for first rotation and would be many folds for next 3 to 4 rotations due to negligible cost of coppiced Eucalyptus. Lowering of water table allowed the farmers to advance sowing of wheat crop by more than two weeks. Due to timely sowing of crop and improvement in soil properties, wheat yield in the inter-space of strip-plantations was 3.4 times the yield in adjacent waterlogged areas without plantation. A view of agroforestry model of biodrainage at Puthi village is shown in Figure 5.

Figure 5 - Agroforestry model of biodrainage. Source: Jeet Ram et al., 2008

The question what should be the optimum spacing of Eucalyptus for strip plantation in agroforestry for achieving maximum benefits in terms of water table draw down, wood production and crop yields was still unanswered. Therefore, above study was continued in the same area by taking strip plantations of clonal *Eucalyptus tereticornis* in paired rows at spacing of 1m x 1m, 1m x 2m and 1 m x 3 m on farm acre boundaries (called killa-lines) spacing resulting in tree population of 300, 150 and 100 trees ha-1 (Dagar et al., 2015 personal communication). Considering wood biomass production, lowering of water table, carbon sequestration and crop productivity, agroforestry biodrainage model of six year rotation having strip plantation of Eucalyptus in paired rows on farm acre line in spacing of 1 m x1 m was found better compared to 1m x 2m and 1mx3m in waterlogged areas of north-east India. After effective results shown by the bio-drainage system in checking waterlogging in Haryana, the Punjab Government is replicating the biodrainage system in 3000 hectares of waterlogged area in Muktsar district (The Tribune, 19th April, 2013).

In Indira Gandhi Nahar Project (IGNP) Rajasthan (India) also tree plantations established along the canal lowered ground water table by 14 m in six years (Kapoor, 2001). The main reasons for the difference in drawdown of ground water table at the two sites (IGNP and Puthi research plot) were the design and density of plantations and the sources of recharge in ground water.

Biodrainage for reclamation of waterlogged deltaic lands of Orissa, India

Biodrainage potential of Casuarinas on land at two sites with groundwater table at 102 and 127 cm in coastal delta, Orissa suffering from waterlogging due to sea water intrusion and Eucalyptus at another two sites on waterlogged soils having groundwater at 150 and 167 cm, respectively caused due to topographical depression were compared by Roy Chowdhury et al (2011). At all the four sites, effects of biodrainage plantation on water table were clear and lowered it by 15 to 25 cm compared to non-vegetated area. As far as efficiency of drainage by plantation or tree water use per se is concerned, greater decline of water table underneath Eucalyptus compared to Casuarina indicated Eucalyptus was found more efficient than Casuarina. Therefore, Eucalyptus plantation was superior in providing drainage relief through intercepting water from deeper soil profile, compared to that under Casuarina plantation in topographically depressed area. This accelerated drainage has helped the farmer to advance rabi cultivation by a period of 15-20 days. Due to this, farmers were able to take watermelon in Casuarina and groundnut in Eucalyptus plantations and earned additional benefit. Yield of rice in Casuarina got improved but in Eucalyptus the crop yields were reduced after two years due to the shading effect and competition with intercrop for nutrients and other resources. Overall, the principle of bio-drainage to lower the rising water table with Eucalyptus and Casuarina vegetation appears promising. The successful intervention with pisciculture, integration of intercrops and crops like watermelon in reclaimed area is also feasible to enhance productivity of areas which otherwise remain sub-productive due to waterlogging. Therefore, high rate transpiring trees like Eucalyptus plantation may be grown for topographically depressed inlands and canal seepage interceptions and may be grown parallel to the field drainage options as an alternative. Similarly salt tolerant tree species like Casuarina may be a good option in coastal waterlogged areas. In Australia also, Casuarina performed better on shallow saline soils (Cramer et al. (1999) for lowering ground water table.

Control of shallow water table by block plantation of Eucalyptus at Kyabram, Australia

Large scale clearing of deep rooted forest trees with shallow-rooted annual crops and pastures followed by introduction of irrigation resulted in rise in water table from 30 m (before clearing) to 2 m or less and development of soil salinity at Kyabram, Australia (Heperman, 1999; Heuperman et al., 2002; Ferdowsian et al., 1996; George et al., 1999). Low returns from the agricultural production systems and the high costs of drainage engineering compelled to go again for planting deep-rooted permanent pastures, crops and trees for achieving a plant water use scenario that more closely approximates that of the pre-clearance situation. Trees lower water table through higher rates of transpiration than shallower rooted and often more salt sensitive crops and also provide timber wood, fuel, fodder to the farmers. During the study period, average rainfall in the region was 480 mm year-1 with an annual average of evaporation 1403 mm. The soils of the sites were loam Natrixeralf, a red brown duplex soil. The site was planted with Eucalyptus, irrigated with freshwater for initial six years and attained increments in height of up to 2.5 m year-1 measured during that period.

The average water table level at the plantation site in February 1977 (two years after tree establishment) was 1.94 m below the surface. Seven years after tree establishment, the trees significantly lowered down the water table underneath the plantation and its impact was observed up to 50 m into the irrigated pasture. As the trees exclude salts during water uptake, salinities in the upper part of the saturated zone (near the water table) underneath the plantation increased. At most of the points in plantation sites, water table salinities increased over the period (1982-1993) reflecting this salt concentration process. In 1993, water table salinities under the trees were clearly higher than outside the plantation. The salt accumulation was recorded between 2.5 and 5.5 m in the profile from the surface.

At another site in the same region decline of the water table was linearly correlated with tree spacing. The decline decreased with increasing tree spacing. The effects were conspicuous after four years of planting. For every 10 percent increase in planted area, the water table was lowered by about 0.4 m.

Integrated management of saline drainage effluent, USA

Disposal of drainage effluent in the San Joaquin Valley, caused selenium toxicity and bio-accumulated salts at high levels in plants and animals enough to cause mortality and to impair reproduction of fish and aquatic birds. Aquatic plants, invertebrates, fish, frogs, snakes, birds and mammals at Kesterson Reservoir contained elevated selenium levels, often averaging a 100-fold increase over samples collected for similar species at reference sites (Ohlendorf, 1989; Ohlendorf and Santolo, 1994). Therefore, combination of bio- and conventional drainage approach to drain water management was designed and demonstrated on a farm in the Central Valley in California (Cervinka et al., 1999).

Farm as a whole covers 620 acres and has 4 salinity zones. Out of these 3 zones each of 157 acres were planted with salt sensitive vegetables and provided with subsurface tile drainage. Similarly, independent drainage systems operated for salt tolerant crops/trees (130 acres) and salt-tolerant grasses (13 acres), whereas shared drainage system for the halophytes (5 acres) and the solar evaporator (2 acres). Vegetables were grown in non-saline zone and irrigated with canal or well water, whereas crops like cotton, alfalfa in low saline zone and received water from tile drainage, tail water (from vegetables), and of canal/well water vegetables. Salt tolerant trees and grasses were grown in moderate saline zone covering two per cent of the project area and irrigated with drainage water from salt tolerant crops. Similarly, saline water from salt tolerant trees and grasses was used in halophytes. This sequential water reuse process productively uses over 90 percent of the drainage water. The remaining drainage water goes into a solar evaporator where water was evaporated and salt crystallized. Sequential reuse of drainage water increased the overall efficiency of water use. The system also prevented on-farm drainage water from contributing to severe regional problems of poor groundwater quality and high water tables. Overall there was a net increase in crop yields and vegetable production grown in non-saline areas. Basically an integrated bio- and conventional drainage system managed irrigation water, drainage water, salt and selenium as resources within the boundaries of the farm and not discharged into rivers or lakes. It seems viable eco-friendly sustainable system for managing water logging and salinity at the farm level. This innovation has great potential for up-scaling in other parts of the world by incorporating location specific adjustments.

Biodrainage potential of Eucalyptus for wastewater disposal

Tree plantations are often expected to use water at higher rates than the shorter vegetation. This is because of greater aerodynamic roughness of tree plantations, clothesline effect in tree rows and deeper rooting system for accessing water down to several metres of soil. Therefore, biodrainage potential of trees having very high transpiration rates can also be exploited for recycling and reuse of wastewater and converting nutrient energy into wood biomass and improving environment. Very high rates of wastewater disposal (0.3–1.0 million litres day-1 ha-1) in *Eucalyptus tereticornis, Leucaena leucocephala* and *Populus deltoids* plantation were reported by Chhabra (1995). Morris and Wehner (1987) reported annual crop factors of 1.4–1.9 times the open pan evaporation (PAN-E) and the maximum daily water-use rates of 20 mm in summer (January) by 3-year-old Eucalyptus plantations irrigated with effluent in arid western Victoria, Australia. With the advancement in measurements of water use, transpiration rate by Eucalyptus plantations estimated by thermo-electric heat pulse method were found to be lower than the reported earlier. In Pakistan, water use to the tune of 0.86*PAN-E was reported from the saline sites (Khanzada et al., 1998; Mahmood et al., 2001). Some of the recent studies (Kallarackal and Somen, 2008; Forrester et al., 2010; Hubbard et al., 2010) show similar results but the overall water use by trees seems to vary a lot with the specific site conditions defining soil type, evaporative demands, stocking density and even the salinity determines the actual water use. In a ten year study conducted at CSSRI, Karnal by Minhas et al. (2015) Eucalyptus plantation irrigated with sewage performed better than the groundwater. Consumptive water coincided with tree growth rates and increased until sixth year of planting and stabilised thereafter. The annual sap flow values ranged between 418–473, 1373–1417 and 1567–1628 mm during 7–10 year of planting under low (163 stems ha^{-1}), recommended (517 stems ha^{-1}) and high (1993 stems ha^{-1}) stocking density respectively. In the nutshell, Eucalyptus plantations can act as potential sites for year round and about 1.5 fold recycling of sewage than the annual crops. Layout set up of the experiment at Karnal farm is depicted in Figure 6.

Figure 6 - Measurement of transpiration rate with sap-flow meter. Source: Jeet Ram et al., 2008

Advantages

The merits of biodrainage technique over the conventional engineering based drainage systems are as given below:

- Farmers although realize benefits of drainage but are too poor to pay cost of drainage, whereas raising biodrainage plantations is relatively less costly and affordable.
- Biodrainage requires no maintenance after initial establishment
- No operational cost, as the plants use their bio-energy in draining out the excess ground water into atmosphere.
- Ecologically safe as drainage effluent is not produced.

- Increase in worth with age instead of depreciation
- Preventive as well as curative system for waterlogging and salinity
- Provides recreational areas and green open spaces, supporting beekeeping (Hadas 2001)
- Sequesters carbon and earn carbon credits
- Moderates the temperature of the surrounding by transpiration thereby proofing for heat and cold waves
- Mitigates greenhouse gases by absorbing CO2 and releasing O2
- Acts as wind break and protects crops in agroforestry system
- Provides higher income to the farmers due to the production of food, fodder, timber, fuel wood and other valuable products. Thinning, based on harvesting about 50% of the slower growing trees, could provide returns even in about five years. The felled trees might be used as a source of biomass for firewood, small poles for agriculture, and/or pulp production, if markets are available. Better performing trees, could be used to produce wood for household and garden furniture (Zohar et al., 2008).
- Biodrainage stabilizes soil on raised bed as highway avenue plantation
- Subsurface drainage in irrigated areas is a collective activity, thus needs appropriate institutional arrangements for farmers' participation (Ritzema et al., 2008). But in case of biodrainage, there is assured people's participation as the biodrainage plantations on farmer's field belong to the individual farmers.
- The improvement in soil salinity and waterlogging provides additional land for cultivation
- Increase in cropping intensity and soil organic carbon build-up
- More choice among arable crops including pulses and oilseed which otherwise are sensitive to waterlogging and salinity
- Timely sowing of crops thus facilitating better yield and profits
- Higher crop yields and nutrient use efficiency
- Increased employment generation and poverty reduction

Constraints

Apart from many advantages, the following limitations of biodrainage may be kept in mind:

- Requires land, may be 10 to 15 % of the total holding of the farmer.
- Requires irrigation for the survival of the trees
- There is a danger of damage in early stages of tree growth
- Tree plantations may not be effective in lowering down the water table in the early growth stages.

- Competition of foliage and roots between trees and crops for light, moisture, nutrient, etc and its effects on co-existing vegetation.
- There is increased activity of the wild animals like blue bull affecting general cultivation
- With age, there would be gradual decrease in capacities of trees for consuming and transpiring water thereby reducing extent of bio-drainage.
- In discharge sites, with evapotranspiration there can be salt accumulation in soil profile which will affect tree growth.
- Where farm holdings are small, obviously landholders are unable to set part of their farm aside for bio drainage activities. Therefore any application of this technique will have to focus on public land.

Future Research and Policy Issues

To further develop the technology of biodrainage, the following issues will need to be considered:

Research issues

- Improving consumptive use of water by trees: There is wide variation in tree water use values because of changes in climatic conditions, type and age of tree species, size of plantation, density of tree plantations (spacing), soil moisture regime, etc. This makes it difficult to select accurate design criteria for biodrainage tree plantings. What should be the optimum density of tree plantings for biodrainage for maximum evapotranspiration per unit area?
- Salt balance and salt tolerance: Further research is required on the mineral absorption by trees and salt-tolerance for estimating salt-balance. The growth of trees and salt-tolerant crops with increasing salt build up in soil profile and consequential impacts on transpiration capacity and excess water removal require further studies in detail.
- Tree species research: Biomass production and water use of desert trees like Prosopis which are high biomass producing and salt tolerant need to be investigated under conditions of abundant water supply.
- High potential biodrainage tree species and their clones/varieties may be identified for specific agro-ecological regions
- Role of highly transpiring Eucalyptus and other trees (bio- drainage) for control of waterlogging, particularly as a preventive seepage control measure in the vicinity of canals and as well as in appropriate agro- forestry models
- Impact of integrated conventional drainage approaches and biodrainage on controlling waterlogging and soil salinity for sustainability of agriculture and environment
- Process based models to predict salinity within the basin under the present and afforested conditions.
- The suitability of biodrainage plantation in shallow saline water table is still in debate.

Policy Issues

- Pilot level studies in waterlogged hotspots for better dissemination of biodrainage technology
- Superior planting stock of trees (clones of Eucalyptus, Casuarina, poplar, bamboos, etc.) which are both fast growing and high transpiring in waterlogged saline soils made available to the farmers
- Provide appropriate credit to the adjoining farmers for raising strip plantations along the canals, high ways and railway for interception of seepage and controlling rising water table.
- Minimum support price policy especially for wood and pulp producing biodrainage plantation to avoid distress sale
- Setting of plywood, paper and pulp industries in rural areas to encourage farmers to go for biodrainage
- Incentives for agencies responsible for undertaking biodrainage programmes
- Awareness and sensitization programs on biodrainage for stakeholders may be organized regularly.

Conclusion

To solve the twin problem of waterlogging and secondary salinization caused due to agricultural development and use of irrigation increasingly demands the biodrainage plantation of trees and salt-tolerant crops as an integrated part of the landscape and farming viewing the cost and environmental issues involved in using the conventional drainage technologies. Plantation of suitable salt tolerant deep rooted fast growing trees with high transpiration rates provides benefits in terms of reclamation of waterlogged area, controlling of water table, improving crop productivity, providing shelter belts, provide additional wood and forest products, and biodiversity. The problems associated with a rise in salinity in the root zone can be effectively delayed using biodrainage systems in semi-arid and arid areas. Biodrainage can be effectively used for water table management both in dry lands and irrigated areas. For better performance biodrainage plantation may also be raised on potentially waterlogged areas to prevent their conversion into waterlogged areas. In areas where the groundwater is sweet and is being subjected to over-exploitation for irrigation and other purposes, resulting in a steep fall in the water table plantation of high biodrainage potential trees might decline water-table further. For the proper planning of bio drainage activities assessment of water and salt balance in the landscape is a major requirement. Apart from advantages, biodrainage has its own limitations also as it requires large area of land, may not be very effective removing salts and performance of plantation is affected by increasing buildup of salinity in soil profile with time. Where bio drainage results in salt accumulation, engineering assistance is needed to make the system sustainable.

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SIMULATION OF WATER FLOW AND SALT TRANSPORT IN DRY DRAINAGE WITH HYDRUS-2D

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Abstract

Sustainable agriculture can help food security. It depends on water and salt balance in the root zone especially in arid and semi-arid regions of the world. Irrigation without drainage is not sustainable. Dry drainage (DD) is rather a new environmentally friendly concept in drainage of arid and semi-arid areas where the irrigation water is much less than the amount to satisfy the extent of the available land. DD was investigated at this study as an environmental and cost-effective alternative technique to the conventional systems. This study was carried out at University of Tehran, Iran, in July 2015 in Lysimetric scale. HYDRUS software was used for DD modeling. Parameters of water flow and salinity transport were optimized by inverse solution of HYDRUS. Results showed that DD could decrease and stabilize soil salinity of the root zone. The salinity at different soil layers of uncropped strips (evaporation strips) was higher than the salinity of cropped strips. Soil salinity at cropped strips was increased downwards while the soil salinity of uncropped strips was increasing upwards. Final soil surface salinity of cropped strips was 1.5 times of the irrigation water salinity while salinity of the soil surface at uncropped strips was reached to 4.5 times of its initial condition after one season. Standard Error and RMSE of observed and simulated volumetric soil water content were 0.26 and 0.104, respectively. Soil salinity of cropped area was predicted better that uncropped area. SE and RMSE of observed and simulated soil salinity were 0.29 and 2.26 (dS/m), respectively. Results of modeling showed that salinity of soil surface at uncropped area was decreased with the passage of time, while surface soil salinity of cropped area remains at its equilibrium.

KEY WORDS: Dry Drainage, Evaporation strip, Solute transport, Sustainable agriculture.

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Introduction

Irrigation sustainability is threatened by soil salinity which in itself is a major threat to food security. IPTRID (2006) estimated that between 10 to 15 percent of irrigated lands suffer from salinity problems with varying degrees throughout the world while a change between 0.5 to 1 percent occurs on nonproductive land each year, and nearly half of all irrigated areas are threatened in the long-term (CISEAU Project).

A report reviewing various estimates of the global extent of salinization on land and water resources concludes that of a total of 230 million ha of irrigated land around the world, some 45 million ha suffer from severe irrigation induced salinity problems (Ghassemi et al, 1995). The global cost of irrigation-induced salinity is estimated as much as US$11 billion per year (Vries et al, 2003).

There are some technical solutions to control soil salinity among which artificial drainage is considered as a major approach. There is a widespread belief that irrigation without drainage is not sustainable, but it is also necessary to consider whether conventional drainage systems are themselves sustainable. While this approach may be suitable for local circumstances, within large contiguous irrigation systems significant economic and environmental limitations may arise (van Schilfgaarde, 1994; Kijne et al., 1998; Ayars and Tanji, 1999; Smedema, 2000; Saysel et al., 2002; Sonuga et al., 2002). Conventional drainage systems have effective roles in the controlling of the water table and preventing soil salinization of irrigated lands; however, thecosts of maintenance and operations and the initial cost for the construction of such drainage systems are very high. In addition, the drainage water in these systems is often saline and sometimes contaminated, and their intrusion into surface water bodies (rivers, lakes, wetlands and so on) creates a number of environmental problems.

In recent years, there have been attempts to identify solutions, which are applicable within environmental constraints and are also economically viable (Hanson, 1989; Gowing and Wyseure, 1992; Asghar, 1996; Sharma and Tyagi, 2004). Currently, the application of alternative methods with due consideration to economical and environmentally friendly aspects instead of conventional ones is highly recommended,. DD is among such methods (Azari, 2004; Konukcu et al., 2006; Khouri et al, 1998; WARDA Annual Report 1997, Akram et al, 2008). DD, which causes parts of the land located adjacent to the cropped land to be retired forever, has been postulated as an alternative (Konukcu et al. 2006). Akram, et al. (2008) studied and modeled DD numerically using SAHYSMOD. They investigated some of the effective factors on DD such as soil hydraulic conductivity, depth to the impermeable layer, depth of the initial water table, the amount and salinity of irrigation water, different evaporation rates of the uncropped area and different ratios of cropped to uncropped widths. The results show that hydraulic conductivity had no effect on the soil salinity of the cropped area and the depth of the water table. The depth of the impermeable layer also had no effect on the water table drop, while it had a considerable effect on the soil salinity of the uncropped strips. They suggested that DD could be considered as a cost effective approach where water is scarce and the land is vast, They also concluded that the effectiveness of DD is higher when the neighboring strips are narrower i.e. 25 m parallel strips are more effective as compared to 50 m ones.

Dry drainage concept

In arid and semi-arid regions, the evaporative demand and the salinity of groundwater may be high and the upward evaporative flux from the saline water table may result in the accumulation of salt with a very high concentration at or near the soil surface. This can occur seasonally on fallow fields or continuously on unirrigated (abandoned) land. The benefits of using this process to control salinity by means of a well -managed evaporative sink area within a ‘‘dry drainage’’ scheme was first proposed by Gowing and Wyseure (1992).

In this method, a part of land in the irrigation scheme is permanently or seasonally fallowed and acts as a sink for excessive irrigation water and the salts transported with the groundwater. The groundwater system creates a pathway for the movement of the excessive irrigation water from the irrigated area to the fallow area. The groundwater table in the fallow area through evaporation declines, resulting in a hydraulic gradient and groundwater exchange between the two areas. Thus the excessive salt will eventually accumulate in the fallow area and the salt balance in the irrigated area can be maintained as depicted in Figure 1.

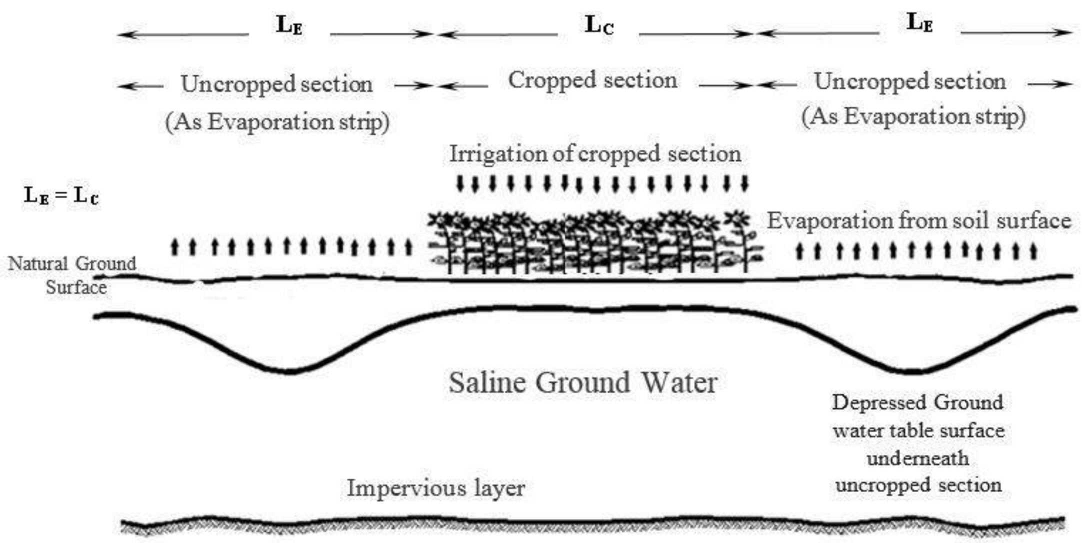

Figure 1: Schematic view of Dry Drainage process

The is the concept of DDis thus if the uncropped area is large enough and evaporation from this area is fast enough, then the necessary balance can be achieved without any artificial drainage.

There are evidences that DD aids in the controlling of soil salinity of the cropped area. In Fergana Valley where there was no outlet of groundwater, the farmers set aside 30-35 percent of the land as fallow land and successfully controll the soil salinity in the irrigated area (Kovda, 1971). In the oasis of Yerqiang River Basintheobservation of the salt balance n in a typical low-lying land over a two year period has shown that the low-lying land accepts 28-44 percent of the excessive salt from irrigation (Shimojima, 1996). DD is also recognized as a sound method by the West

Africa Rice Development Association (Gowing, 1992 and WARDA Annual Report, 1997). Numerical studies on hypothetical field-scale DD examples in the San Joaquin Valley of California, U.S.A were successfully carried out (Khouri, 1998).

There is evidence that some parts of the Indus Basin in Pakistan have already benefited from DD systems and the practical significance of this mechanism has been recognized for some time (Middleton et al., 1966). Doosti et al (2014) recommended an equal ratio of cropped section to uncropped section (50 to 50 percent) with the lowest risk.

Objective of the study

The major objective of this study was to investigate water and salt transport from a cropped to neighboring uncropped area in a research lysimetric scale. In addition, HYDRUS calibration and the optimization of the water flow and salt transport parameters were additional aims of this study. Another goal was to clarify whether a solute transport model (in this case HYDRUS 2D) is capable of simulating the dry drainage concept.

Materials and method

Study location

The study was carried out at research field of the Aburaihan College at the - University of Tehran, Iran (attitude: 35˚ 29' 1'', Longitude: 51˚ 40' 59"). Research open space lysimeters were used to collect the necessary data for interpreting and evaluating the effects of DD on the lowering of soil salinity in the root zone while keeping the water table at its desired depth.

Field experiment

The Lysimeter was made of black iron sheets (the surface of one square meter and a depth of one meter) with thickness of 2 mm. Stainless materials were used for preventing rusting and to ensure the entire inner surface of the lysimeter was stained using pool color (creating a special stainless steel surface with a blue color). At first, four rows of capped holes at one side of the lysimeter were used to collect and measure data during the experiment. However, due to the soil texture, measuring via installed holes was not possible, thus vertical measurements were done from the soil surface. A Schematic view of the research lysimeter is shown in Figure 2. According to previous studies, The cropped section (cropped area) and the uncropped section (evaporation area) were separated equally with an iron blade of 8 cm height.

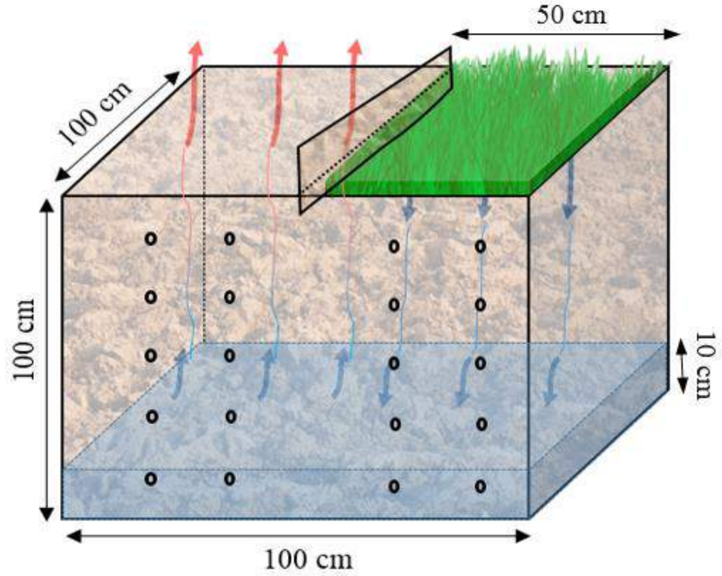

Figure 2: Schematic view of the research lysimeter

The Lysimeter was installed in the soil and a white foam board (2 cm thickness) was used for insulating and preventing direct contact of sunlight to the outside of the lysimeter's surface.

A large sifter (surface of 2m×2m and sieve size of 1 cm) was used to prepare the required 1.5 tons of soil to fill the lysimeter. Sufficient irrigation water was applied to keep the density of the soil at its natural condition. Then four soil samples were collected to measure the soil salinity at its initial condition. The Sieve analysis showed the soil was loam (Table1). The soil of the cropped zone was irrigated before the starting experiment to keep the water table at 90 cm depth from the soil surface. The Salinity of the shallow groundwater was 55 dS/m. Two observation wells were used, each to one side (cropped section and uncropped section) to measure the water table depth. Sport rolled lawn was planted in the cropped section as the reference crop.

Table1: Summery of soil physical and chemical parameters

Soil Texture	Bulk density	Soil particles (%)			$EC_{e\ initial}$
	(gr/cm^3)	Clay	Silt	Sand	(dS/m)
Loam	1.33	19	35.5	45.5	5.1

Measuring irrigation water requirement and preparing saline water

The amount of irrigation water was determined based on water table drawdown. Irrigation was done daily to compensate the drop of the water table and keep the water table nearly constant. Natural drainage water of Qazvin's marshland was used to prepare saline irrigation water. Every night, enough saline water was prepared for irrigation by diluting the marsh water in order to reach to an irrigation water with a salinity of 3 dS/m. A portable EC meter was used for measuring and recording water salinity. The Experiment started on July 26, 2015 and continued for 70 days. Total irrigation, Pan Evaporation and rainfall during these 70 days was 658, 587 and 17 mm, respectively (Figure 3).

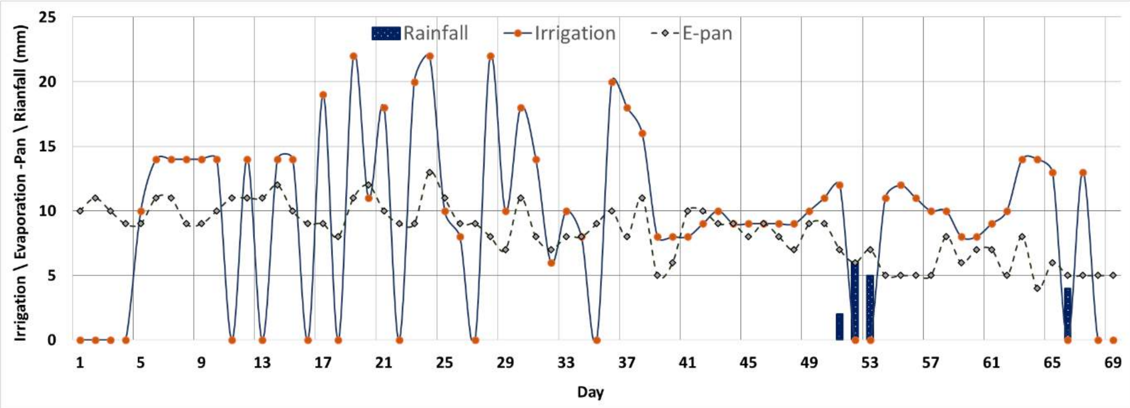

Figure 3: The amount of irrigation depths and evaporation from Pan during the experiment

Measuring soil moisture and salinity during experiment

Measurements included the gravimetric water content and salinity of the saturated paste extract (ECs) at four depths (0-20, 20-40, 40-60 and 60-80 cm from the soil surface). These measurements were done for both sides (cropped and uncropped section) and four times (days 1, 21, 35 and 68 after starting the experiment).

HYDRUS

HYDRUS is a general software package for simulating water, heat, and solute movement for a two/ three dimensional variably saturated porous media. HYDRUS numerically solves the Richard's equation for saturated-unsaturated water flow and the convection-dispersion equation for heat and solute transport. The HYDRUS-2D model (Šimůnek et al. 1999) uses the two dimensional form of Richards' equation incorporates a sink term to account for water uptake by plant roots as below:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \qquad (1)$$

Where θ is the volumetric water content (dimensionless); h is the pressure head [L]; S is a sink term [T^{-1}]; x_i and x_j are spatial coordinates [L]; t is time [T]; K_{ij}^{A} are components of a dimensionless anisotropy tensor K^A; and K is unsaturated hydraulic conductivity function [LT^{-1}].

The HYDRUS-2D model implements the soil-hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) to describe the soil water retention curve, θ(h), and the unsaturated hydraulic conductivity function, K(h), respectively:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (2)$$

$$K(h) = K_s\, S_e^{l}\left(1 - \left(1 - S_e^{1/m}\right)^m\right)^2 \qquad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad m = 1 - \frac{1}{n}, \quad n > 1 \tag{4}$$

where θ_r and θ_s denote the residual and saturated water content, respectively (dimensionless); α is inverse of the air-entry value [L^{-1}]; K_s is the saturated hydraulic conductivity [LT^{-1}]; n is the pore-size distribution index (dimensionless); S_e is effective water content (dimensionless); and *l* is pore-connectivity parameter (dimensionless), with an estimated value of 0.5, resulting from averaging conditions in a range of soils (Mualem 1976).

HYDRUS-2D numerically solves the convection-diffusion equation with zero- and first-order reaction and sink terms. The Galerkin finite-element method is used in this model to solve the governing equation subjected to appropriate initial and boundary conditions. In this study, the general form of the equation was used to simulate salinity movement in soil by solving the following equation:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}^{w} \frac{\partial c}{\partial x_i}\right) - \frac{\partial q_i c}{\partial x_i} \tag{5}$$

Where c is the salinity concentration in the soil [$M L^{-3}$]; q_i is i^{th} component of the volumetric flux [LT^{-1}]; D_{ij} is the dispersion coefficient tensor [L^2T^{-1}]. D_{ij} can be defined as follows:

$$\theta D_{ij}^{w} = D_T \, |q| \, \delta_{ij} + (D_L - D_T) \frac{q_j q_i}{|q|} + \theta D_w \, \tau_w \, \delta_{ij} \tag{6}$$

Where D_w is the molecular diffusion coefficient in free water [L^2T^{-1}]; τ_w is the tortuosity factor (dimensionless); δ_{ij} is the Kronecker delta function ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$); D_L and D_T are the longitudinal and transversal dispersivities [L].

Appropriate spatial discretization is crucial to avoid numerical oscillations and achieve acceptable mass balance error (Šimůnek et al. 1999; Valiantzas et al. 2011). At the soil surface (with sharp gradients), the discretization decreased to approximately 1 cm and in the other parts it was approximately 3–4 cm. As suggested in the manual of the HYDRUS-2D model for minimizing or eliminating numerical oscillations, the criterion "P.Cr ≤ 2" was used, in which P and Cr are the Peclet and Courant (Cr) numbers, respectively.

The simulation geometry and boundary conditions for DD at lysimeter are presented in Figure 4.

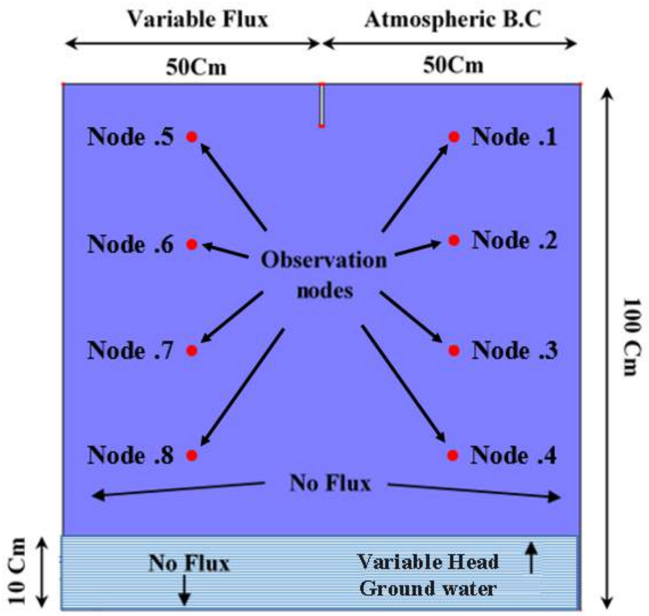

Figure 4: Geometry and boundary conditions of dry drainage used in HYDRUS

Bare soil evaporation from the uncropped area was estimated by multiplying the Ep (evaporation from pan) and Kp (empirical coefficient). Kp was defined as the result of water balance during simulation. A number of water flow and salinity transport parameters were estimated using an inverse solution procedure implementing the Levenberg-Marquardt optimization module built-in HYDRUS- 2D (Šimůnek et al. 1999). The inverse method is based on minimizing a suitable objective function, which expresses the discrepancy between the observed and predicted model values.

Results and discussion

Field experiment results

In general, soil salinity in the uncropped section was more than the soil salinity of the cropped section in all soil layers. In the cropped section, soil salinity increased downwards. However, over time, the salinity of different layers of the cropped section increased and reached to equilibrium after about 35 days; in as such that the soil salinity of the top soil (0-20 cm) at the beginning of the experiment was 2 dS/m and after 35 days this amount increased to about twice that of the irrigation water salinity (about 6 dS/m) and remained constant until the end of the experiment.

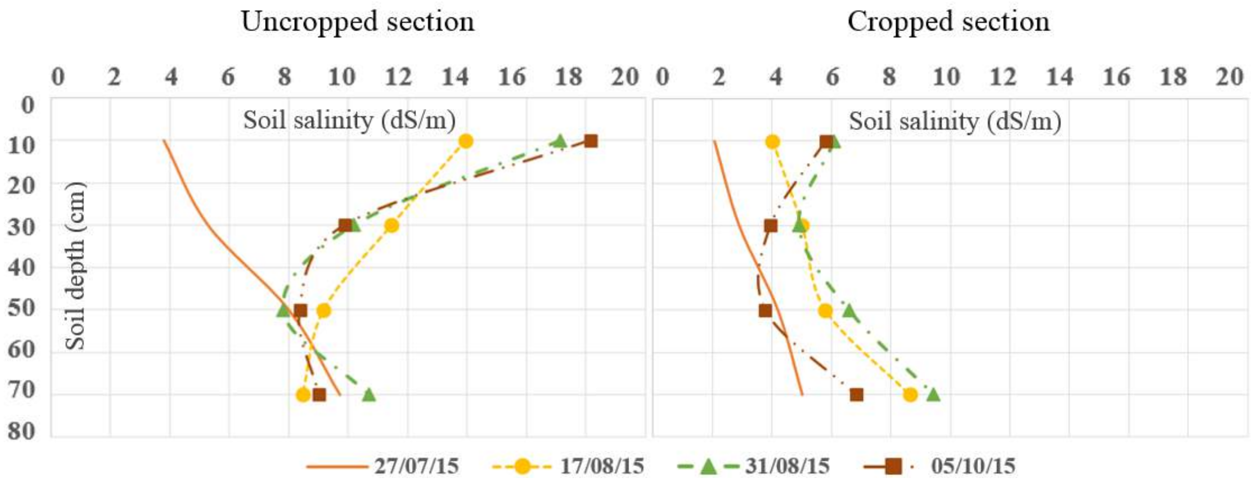

Figure 5: Soil salinity changes with time in cropped and uncropped sections

Initial soil salinity of the uncropped section was increasing downwards which conversed (decreased from up to down) after starting irrigation with saline water. The results showed that during the experiment, top soil salinity was higher than the deep soil in the uncropped section. Changes in salinity at different depths of this section indicate that salinity movement is upward (inreverse tothe downward movement of salinity in the cropped section). Over time, the soil salinity of each layer increases but the rate of this increase drops, which indicates salinity has reached its equilibrium. Most changes to the soil salinity is related to the top soil of the uncropped section. It has increased four times, from 4 dS/m at the beginning to about 18 dS/m at the end of the experiment.

Figure. 6 shows the soil salinity differences (SSD) at equal depths of the cropped and uncropped sections over time. It can be concluded, however, that SSD of the top layer is lower than other layers at the beginning of the experiment and it is higher than the other layers at the end of the test. Over time, the slope of SSD is reduced in bothsections and the soil salinity reaches its equilibrium. SSD of the lower layers are reduced during the experiment and at the end of the test, the least amount of SSD in the 60-80 cm layer was recorded.

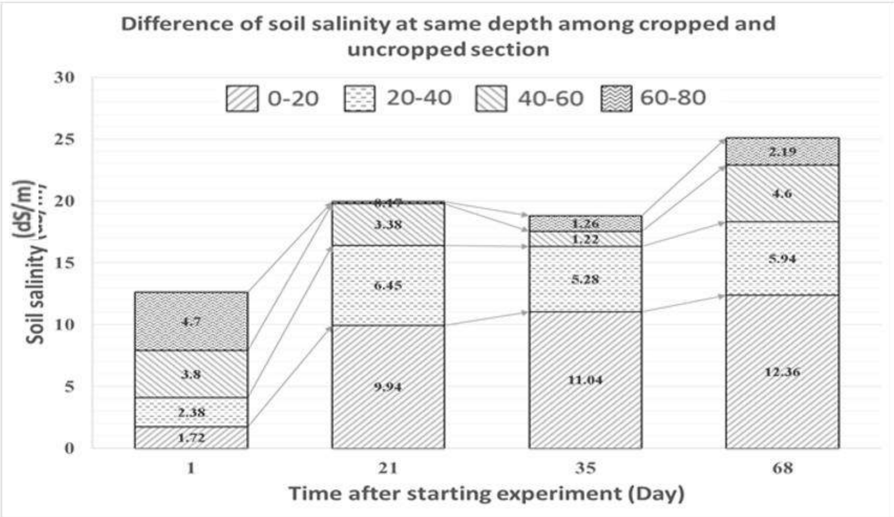

Figure 6: Soil salinity difference (SSD) at the same depths in cropped and uncropped section

Modeling results

The optimized soil water flow and the salinity transport parameters were shown in Table 2. HYDRUS was rerun with an optimized parameters. The results of the comparing of measured and modeled soil water content and soil salinity are shown in Figures 7, 8 and 9.

Table 2: HYDRUS outputs of optimized and statistical parameters

	hydraulic parameters					Solute transport parameters				
Parameters	θr (m^3/m^3)	θs (m^3/m^3)	α (mm^{-1})	n (-)	Ks (mmh^{-1})	D_L (mm)	D_T (mm)	D_w (mm^2h^{-1})	R^2 (-)	NRMSE (-)
Value	0.011	0.498	0.0017	1.53	5.05	317.9	1.42	2.55	0.987	0.34

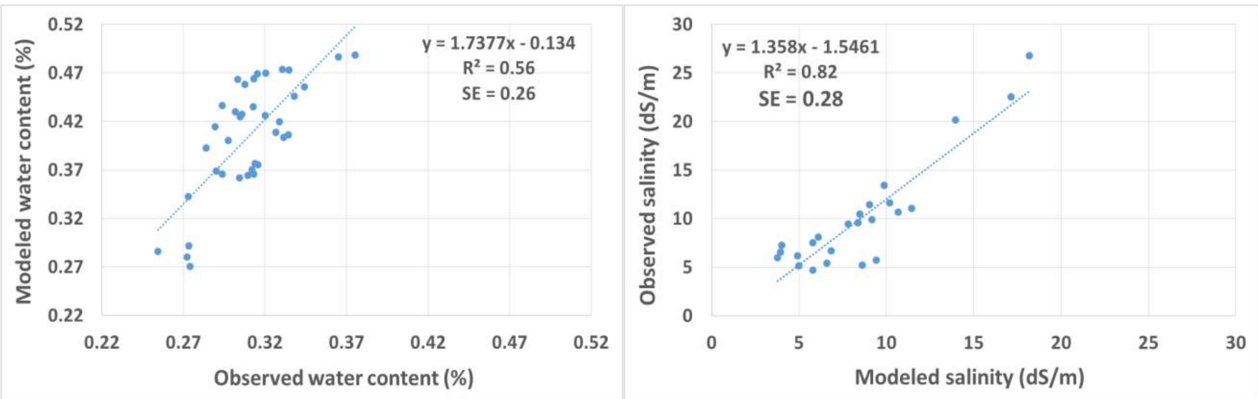

Figure 7: Comparison observed and modeled soil water content and soil salinity

The results show that the modeling of soil water content for both cropped and uncropped areas was good. The Existence of a shallow water table leads to high soil moisture content for both sides and results into a low range of observed soil water content. However, HYDRUS finds the best parameters of water flow and salinity transport using an inverse solution method. The SE and RMSE of observed and modeled soil water content were 0.26 and 0.104 (m3/m3) respectively. The soil salinity of cropped area was simulated better than that of the uncropped area. The SE and RMSE of the observed and modeled soil salinity were 0.29 and 2.26(dS/m), respectively.

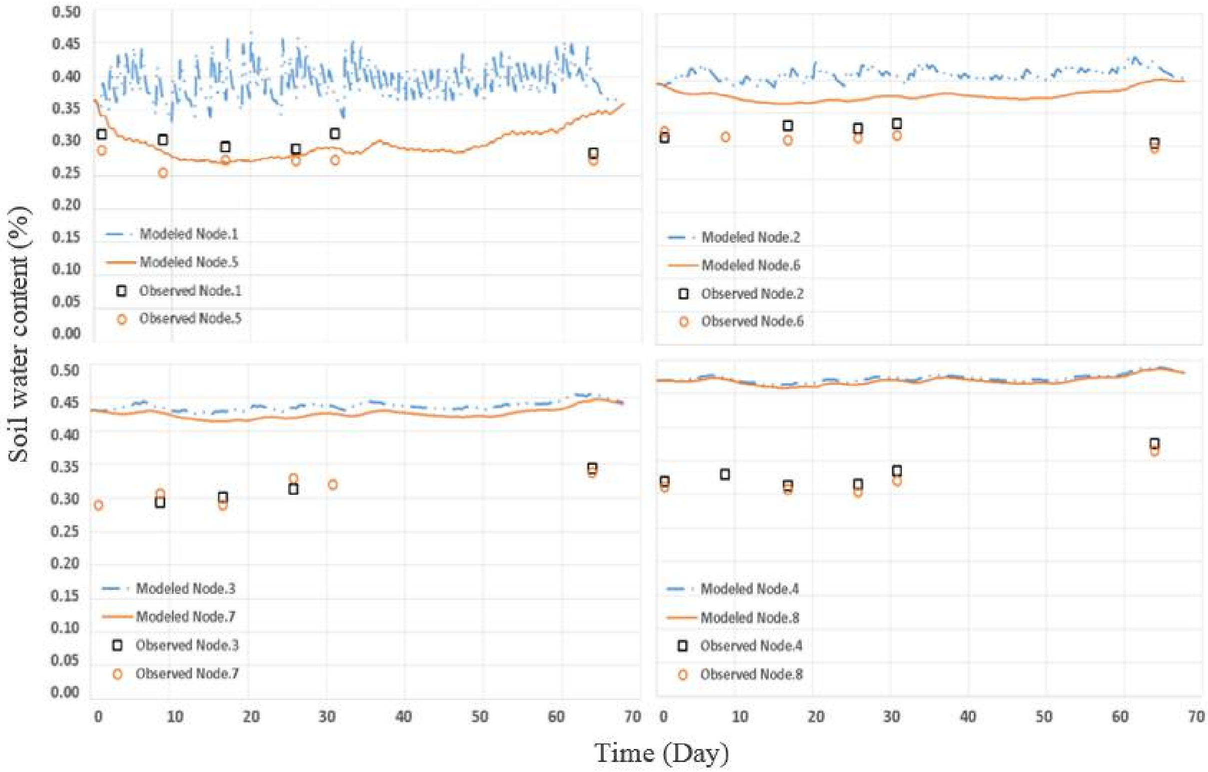

Figure 8: Measured and simulated water content of different layers

The results of the model show that the salinity of the soil surface in the uncropped area increases with time, while the surface soil salinity of the cropped area reached equilibrium. In other words, DD can stabilize soil salinity of the root zone by transporting salt from the irrigation area to an evaporation area (from cropped to uncropped area).

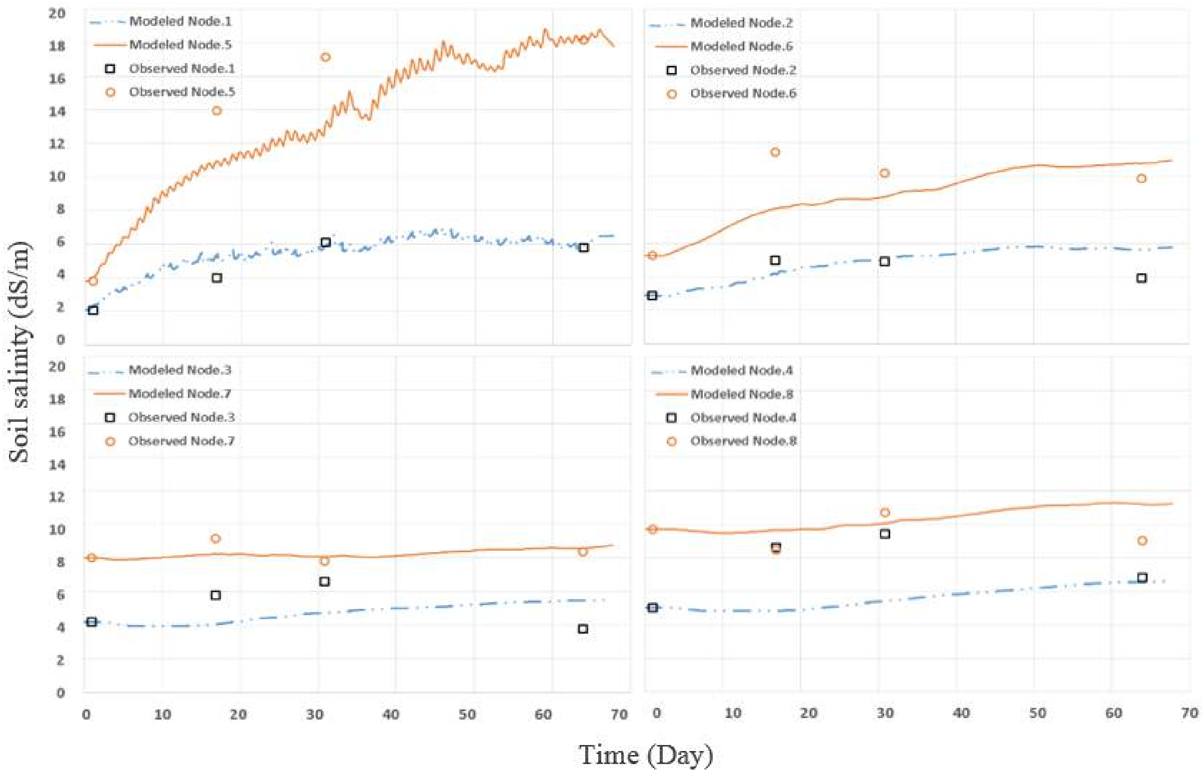

Figure 9: Measured and simulated soil salinity of different layers

Conclusion

There is no clear physiological analysis for Sport rolled lawn ; hence, it was not possible to discuss plant conditions scientifically. However, it appeared to be with no water stress. The salinity of the root depth was low without any sign of soil salinity. DD is able to decrease and stablize the soil salinity of the root zone by transporting salt from an irrigation area to an evaporation area. Salinity variation and water flow direction in this study was matched with the fundamentals of DD (Gowing and Wyseure, 1992). DD can be modeled well using HYDRUS. Although at Lysimetric scale, the low range of the observed soil water content exists as a result of a shallow water table, this limitation does not exist on a large scale and the modeling of DD can be done with more confidence.

Acknowledgement

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5

Topic 5: Irrigation and Drainage Management

DRAINAGE SYSTEM IN IRRIGATED SECTOR KEY FOR BETTER WATER MANAGEMENT GEZIRA SCHEME – SUDAN

Mufadal E. M. Ahmed[1,*], Abu Obieda B. Ahmed[2]

Abstract

Agriculture remains a key element and pillar of Sudanese life, and represents the main driving force for its economy and as an income generating sector for more than 50% of households. This sector accounts for about 31% of GDP (Central Bank of Sudan CBOS-report, 2015); The irrigated subsector as part of the agricultural sector is responsible for the production of cash crops (cotton and sugar cane,..) and cereals. In mega irrigation schemes such as the Gezira Irrigation Scheme (GIS)- the forerunner of all major schemes in Sudan with an area of about 0.882 million ha-the drainage (surface) system plays a significant role in tandem with the irrigation system. Water logging and hence the significant reduction in crop production, coupled with negative environmental impacts are considered as strong obstacles against harnessing the available water resources for better livelihoods.

This paper is a contribution to the Sudaese governmen's effort towards upgrading GIS. The drainage system within the scheme did not receive enough attention and witnessed severe deterioration due to several reasons that occurred over the operational lifetime of the scheme, which in itself accelerated the spread of silt and weeds in the network system of the scheme.

The paper discusses and attempts to diagnose, and analyze the performance of the GIS drainage system by identifying its arrangement, design, capacities, and adequacy to contribute a solution to water management and constraints to sustainable development. In addition it provides a set of amendments and improvements to the existing system including a revision of its design criteria and how that improvement, if implemented properly, can result in better water management and providing an environment for production.

KEY WORDS: Surface drainage, Water logging, Design criteria, Gezira Irrigation Scheme, Water management

Introduction

Sudan, with an area of 1,882,000 square kilometers, and a population of about 40 million is an agricultural-based economy; that agriculture remains a key sector and the core of Sudan life, is representing the main driving force for its economy and as an income generating sector for more than 50% of households. The sector accounts for about 31% of GDP (Central Bank of Sudan

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CBOS-report, 2015). *The irrigated agriculture sub-sector* is also a key factor in agriculture, which contributes to the stability of the country agricultural production, and includes 100% production of sugar cane and more than 80% of cotton.

The GIS is huge in size and dominates the entire irrigated subsector in Sudan, approximately 47% of the entire total irrigated area in Sudan (Plusquellec, 1990).

The Gezira scheme was designed in the 1920s after prolonged experiments had been carried out on a prototype scale. It was designed with the main objective of producing cotton, as a single cash crop. The irrigation and drainage of the scheme *was* laid out to suit the size of tenancy and crop rotation. The flat and featureless topography was favorable to the adoption of regular gridiron layout. The basic unit is a group of four adjacent fields of 90 fed (1 feddans=0.38 ha) each called a Number. One crop is grown on each number following the four rotation system. Each number is divided into 18 tenant fields of 5 fed (called hawasha),(Farmers do not own their lands; they are tenants and arrangements for endorsement of land ownership is a very complicated problem since the 1921 Gezira Land Ordinance). The tenants fields are divided by a network of cross-bunds for irrigation by basins (now it transferred to furrow), (Plusquellec, 1990). (fig. 1& 2 shows the scheme location and the standard field layout).

The irrigation system comprises twin main canals running from head-works at Sennar dam with a design combined capacity of 354m^3/s, and a network of irrigation and drainage canals. The main, branch and major canals are designed as regime conveyance channels. The minor canals are designed for distributing water continuously flowing from the major canals. According to the design principle the field outlet gates serving the "numbers" are open 12 hours per day at a nominal flow of 116 1/s (5,000 m^3/12 hour). The irrigation and drainage system main features include (Plusquellec 1990):

- 2 main canals of total length of 261 km with conveyance capacity ranging from 168 and 186 m^3/s at headwork to 10 m^3/s at the tail; 11 branch canals of total length of 651 km with conveyance capacity ranging from 25 to 120 m^3/s.
- 107 major canals of total length 1,652 km with carrying capacity ranging from 1.5 to 15 m^3/s; and 1,498 minor canals of total length of 8,119 km, a delivery capacity ranging from 0.5 to 1.5 m^3/s; 29,000 water courses called “Abu Ashreens” Abu XX of total length of 40,000 km with 116 L/s capacity; and 350,000 field channel called “Abu Sitta” (Abu VI) of total length of 100,000 km with 50 L/s capacity.
- All canals have headwork and cross-regulators (types are: sluice gates, well head regulator and pipe regulators, and Butcher weirs).
- The drainage system comprises:
  - ❖ The present surface runoff drainage system consists of minor surface drains of total length of about 6,000 km and major drains totaling about 1,500 km in length
  - ❖ Escape drains in the Gezira Main Canal with total escape capacity of 67m^3/s; and Protective drain of 130 km.

Background

Since its establishment, the GIS have experienced many changes. The Sudan Gezira Board (SGB) replaced the former managing Sudan Plantation Syndicate in 1950. Production relations have undergone several modifications. The Joint Account System (JAS) was modified in 1946, 1950 and in 1970, and was replaced by the Individual Account System (IAS) in 1980/81 up to date. (A.M.Eldaw, 2004).

The Cropping System

Based on the tenancy agreement, decisions on crop choice, crop mix and crop rotation are the domain of the Gezira Board. The Agricultural Committee (a sub-committee of the Board of Directors) is the body that makes decisions on crop rotation, though with technical support include all agricultural activities. The initial crop mix in the Gezira Scheme included, besides cotton as a major crop, sorghum and lubia (dolichos lablab). These crops were grown in a three-course rotation: cotton–sorghum/lubia–fallow. The crop mix and crop rotation were subjected to various changes for technical and economic reasons in the course of time between the early 1930s and the early 2000s. Following the intensification policy in 1975/76, a unified four-course rotation was adopted all over the irrigated area. This rotation was expanded in the early 1980s to a five-course rotation to introduce fodder cultivation as a basis for the integration of livestock production into the scheme's cropping system but not adopted. All these developments lead to many changes of the cropping rotation adopted (A. M. Eldaw, 2004). (Table1). Crop Rotation in the Gezira Scheme after 2005 Act adoption is not defined as liberization of cropping system allow farmers to cultivate freely(not obliged), and SGB is just planning and supervising.

Table 1. Development of Planned Crop Rotation in the Gezira Scheme

Season	Crop rotation	Land use %	Remarks
Gezira: 1925/26– 1930/31	C – S/L – F	66.30	
1931/32– 1974/75	1931/32 First change crop rotation in crop rotation to combat cotton infestation, followed by many changes affected by diversification policy	33.30, 44.75, and 69.75	eight course rotation was established
1975/76– 1980/81	C – W – G/S – F	75.00	
1981/82– 2005/06	C – W – G/S – F – Fo	75.00	Fo-Not adopted
Managil extension: 1975/76 - 1980/81	C – W – G/S – F	100.00	
1981/82 – 2005/06	C – W – G/S – F – Fo	75.00	Fo-Not adopted

C = cotton; F = fallow; Fo = fodder; G = groundnuts; L = lubia;; S = sorghum; W = wheat
Source: Galal, M. Y. (1997), remarks are added to the table, and recent seasons are amended

Scheme Operation

Before the adoption of 2005 Gezira Act the operation of the scheme is centrally controlled: The management is divided between the Ministry of Irrigation (MOI) which is responsible for the irrigation network (23 subdivisions) and the Sudan Gezira Board ((SGB), 106 blocks), which is responsible for agricultural operation. The water orders (or indents) are passed to the MOI engineers, summed out throughout the system up to head-works at Sennar dam..

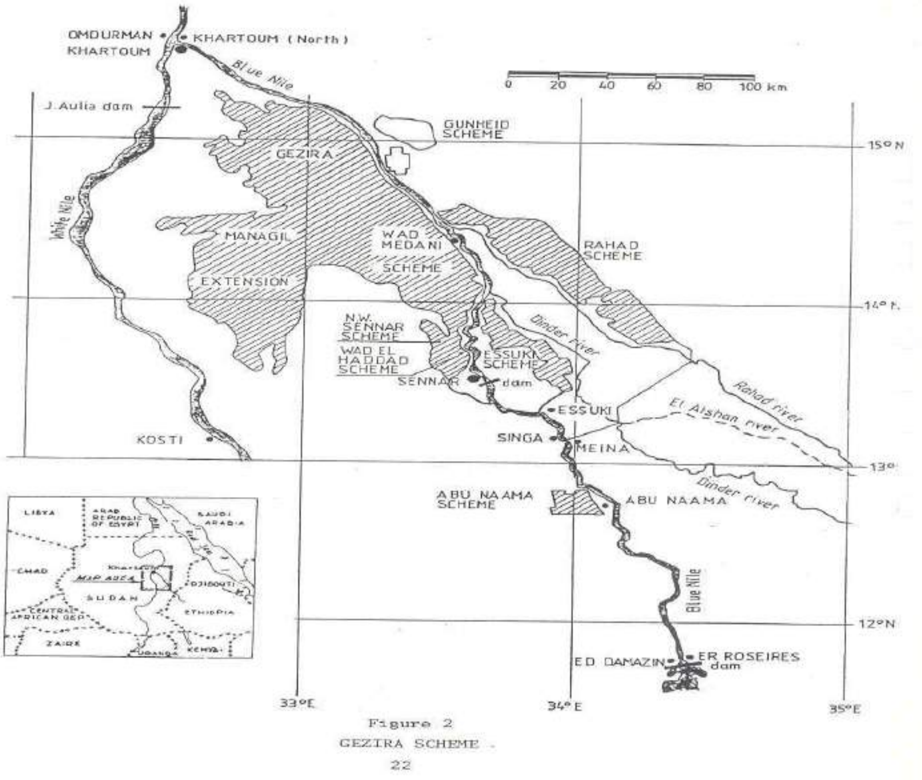

Figure 1. Gezira irrigation scheme location map **(source: david t. Williams, 1988,)**

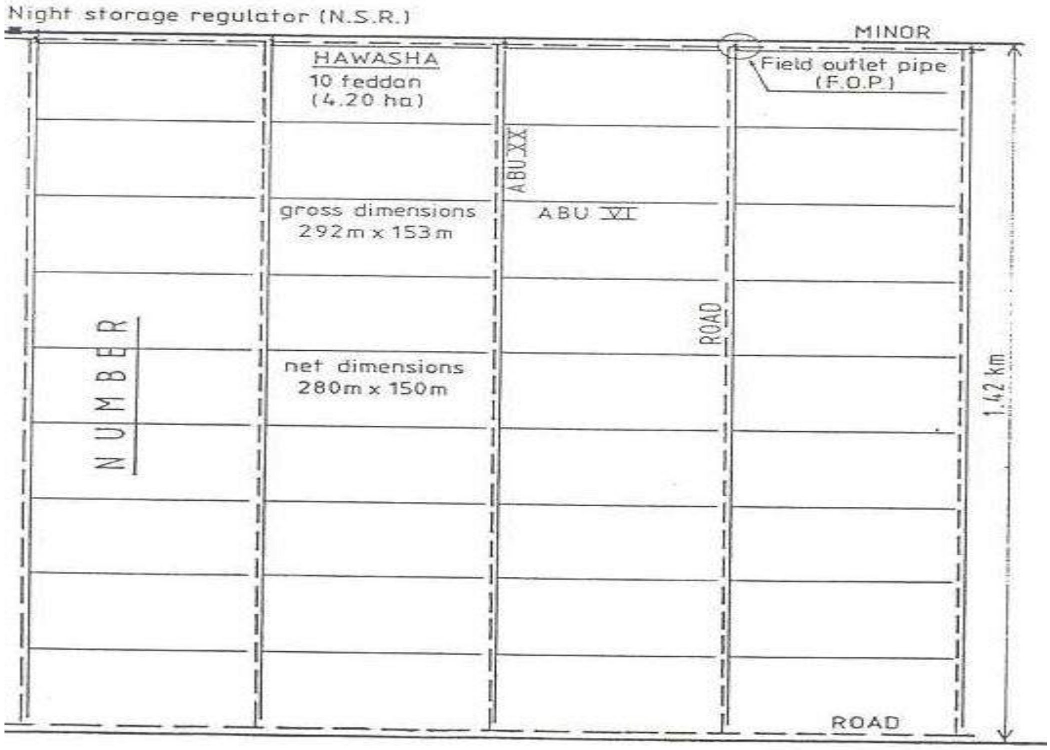

Figure 2. Gis standard typical field layout (source: david t. Williams, 1988,)

MOI(Ministry of Irrigation) delivers the required discharge up to the head of the minor canals, and SGB is responsible for the delivery of water to the tenants.

The Gezira scheme is not a sophisticated one by present day standards. The design, however, took the best advantage of some favorable and unique features of Gezira: (1) The flat topography; and (2) the adopted tenancy system. The adoption of the night storage system resolved the issue of night irrigation found in many schemes, and provide a remarkable solution to the complex problem of adjusting water releases at the head-works. A negative characteristic of the minor canal, which was probably overlooked, is its ability to trap the silt released into the system. For about 40 years, the Gezira scheme was operated satisfactorily on the basis of the original design and operational concept. The management of GIS ran into problems in the early 1970's shortly after the scheme reached its present extension and application of intensification. (Plusquellec,1990). Because of the lack of financial resources, MOI was not able to cope with removal of silt and weed clearance. Poor maintenance led to a reduction in the transit capacity of canals, wear out of regulatory system.

The Drainage System in the Scheme

Basically, the scheme design surface runoff drainage system consists of minor surface drains of about 7,800 km length, collective or major drains of about 2900 km length, escape drains, in Gezira Scheme main canals; it is characterized by a very limited capacity for runoff of surplus water tables 2 &3 shows drainage capacities.

Table 2. Scheme Escape Drains (sources: Gezira Regulation Handbook)

Item	Escape	Authorized Capacity (Mm^3/day)	Remarks
1	K.57 Escape	1.80	closed
2	K.77- Wad El Nau	0.40	closed
3	K. 108 –Beika Escape	0.90	Feed University of Gezira farm
4	K.169-Abu Usher	1.20	
5	Managil escape (k65)	1.5	closed
	Total	5.80	

Table3. Scheme Collective, Protective, and Minor Drains

Description	Scheme Administrative Divisions				Scheme Total
	North Gezira	South Gezira	East Managil	West Managil	
Total Irrigated Areas(fed)	834,000	435,274	445,726	485,000	2,200,000*
T. length of minor drains(km)	1,825	2,710	1,465	1,865	7,865
No of collective Drains	20	35	16	17	88
T. length of collective (km)	602	843	471	957	2,873
Shawal protective drain-in km					130

* This total includes pump station schemes within Gezira, like Hurga & Nur el Din,. etc),
Source: Ministry of Water Resources, Irrigation and Electricity (MOWRIE).

The original design of the Gezira Irrigation System recognized that because of the nature of the soil and absence of a high water table, there was no need for, and indeed no means of providing sub-surface drainage of the fields. The only need for drainage, therefore, was for dealing with surface runoff from rainfall or excess irrigation. The system of drains which exists in various areas in the Gezira has been provided with the object of carrying off rainwater from the land as soon as possible after it has fallen. Although there are no field drains parallel to the Abu XX to take runoff from the fields; Minor drains settings (figure2), are run parallel to minor canals discharging into collector drains which generally follow the lines of natural drainage and lead the runoff water to outfalls. The collective drains ideally outfall beyond the cultivation boundaries to natural drainage lines (depressions) or thence to the Blue or White Nile. However, several drains terminate in large local depressions usually on land which is unsuitable for agriculture; after that the runoff water is allowed to pond up and then evaporate.

The drainage system design capacities were originally based on empirical formulae derived from experience of basin irrigation according to the relationship: (MOI -Design Sheet File DSF)

$\mathbf{Q = CA^{2/3}}$, Where:

Q = discharge in m^3/day

A = Catchment area in fed (Feddan)

C = runoff factor, a constant depending on intensity of rain, soil permeability, geographical zone and other climatic factors (=150 for North of the Scheme and 270 for far South of the Scheme) (according to DSF specification). This relationship is developed for the cultivated area under basin irrigation and assumes considerable storage of potential runoff on the field and some storage in fallow area.

The drainage channel system was set as complementary to the canal system. Minor drains and collective drains channel sections are designed based upon the Manning equation (principally based on 0.20 m free board from ground level for various slopes of minor drains and side slope 1:1 –DSF and other parameters are set accordingly).

The Problem and Constrains

Changes in agricultural field practices from basin irrigation to furrow system intensify the flow of surface water (rain or excess of irrigation) to the limited capacity drainage system, and the relationship (formula) used for design is no longer valid for application. Also the existing irrigation and drainage system is suffering since the late 1970's, when the Sudan Government was very much concerned about the general decline of the irrigated agriculture production particularly in the GIS. It was agreed to initiate a rehabilitation program (with the World Bank). The rehabilitation project initiated in 1984 concentrated on the restoration of the irrigation system and a package for rehabilitation of the drainage system were included within other components as:

"*To restore the drainage systems to original design standards the project includes removal of an estimated 3.0 million m^3 of silt from major(collective) drains, construction of 190 km of new drain and rehabilitation of 4,000 km of silted up minor drains to their design sections. Five new drainage pumping station will replace the old ones which are out of operation. Two new siphons and six hundred road crossings along the major drains are also to be installed*", (World Bank, report 1994)

Unfortunately the two important items namely: Silt clearance of minor drains, and excavation of new minor drains were not executed, and other items are not fully implemented (no records). Accordingly the present drainage running without field and minor drains (the minor drains are completely buried and not exist).

The working drainage system inside the Scheme is only collective drains with very limited capacities. Also depressions where most of the collector drains outfall have been silted up, covered with grass and partially with forest do no longer receive the drainage water effectively even part of the them are used as township for labors (Kanabi). Eventually, the drainage water from collective drains inundates the nearby cultivated fields (water logging). This is also coupled with excess water from irrigation (as wear out of regulatory system), and in the absence minor drains the areas along & around collective drains are infested with weeds. Leading to a wide spread of water covering other fields & field roads. It is also very common that farmers and villagers are suffering a lot during the rainy season even to reach their farms. The results are a very bad environment for production. Table 4 below shows the main impacts in the last rainy season (2016), and Malaria infection as recorded by health authorities.

Table 4. Areas of main crops affected in the last rainy season (Jul – Sep 2016), and Health Impacts*

Item	Crop**	Damaged Crop Area(fed)	Inundated Crop Area(fed)	Total Crop Area Affected(fed)
1	Cotton	2,449	3,240	5,689
2	Groundnut	12,022	4,537	16,559
3	Sorghum	29,141	14,460	43,601
4	G . Total	43,612	22,237	65,849

* Average Malaria infection inside Gezira during rainy season increases by about 2.7%(source- Malaria Treatment Department – Gezira State Ministry of Health, Wad-Medani)

**Other crops no records, Source of data is SGB.

Also the Gezira Scheme has experienced many administration changes in the early 2000s, especially after adoption of 2005 Act (2009-2015), where the irrigation sector transferred from MOI to Ministry of Agriculture and liberation of cropping in the GIS without a comprehensive look to the consequences as

- A non defined cropping rotation(many crops per one block or Number)

- Interruption of indent-supply procedure(high indent for long periods almost full season), and water logging (very poor water management)

The results are an improper use of the system, and inefficient water management.

Effect of crop liberization: Before adoption of 2005 Act, the working crop rotation is 4 courses, which indicate that during rainy season 50% of the area will be not under cultivation (25% of cultivable area is fallow + 25% is for winter crops), and so 50% of the area is receiving ponding or storage of drainage water (especially rain cut irrigation water). Changing to 5 course rotation, theoretically 60% of the area will be under cultivation(10% excess); but in reality (and after adoption of 2005 Act) is 75% will be under cultivation(no fallow, only winter crop area or not yet planted is remained) leading to reduction of ponding(storage capacity) areas by 25%.

Methodology and Material

Approaches

The problems related to the drainage system in the GIS have many dimensions such as technical, managerial (agricultural policy), and institutional complications. The approach proposed in this paper is based on the investigation, revision & check, and analysis for the real causes of the problem taking into consideration the following:

- The scheme network is huge and it is not possible to cover a wider range for such a system in this part of the study.
- The approach concept of investigation and survey will select an area of study, collect basic data, information and carry out all checks and analysis for the selected area.
- The approach will deals with the application of developed techniques or formula following the design of the system and proved to be suitable to the system.
- Problems related to the system and not existing within the selected area, there will be a reference to that; and analysis results and solution proposed will be drawn with recommendations for the whole drainage system in the scheme.

In the essence, this approach returns to the original objectives of the study and attempts to ensure that the results and recommendations can be viable in practice.

Investigation and Revision

This investigation and revision for drainage design flow rate in the Gezira Scheme is carried out concurrently with a reference to a report of a comprehensive study conducted to MOI by Sir M. MacDonald & Partners Consulting Engineer for Rahad Project under design review of irrigation canal and drainage system in 1977. Also the above report (*design review Report)* was referred to two reports as follows:

(i) An earlier report: (Roseires pre-investment survey, Report No.5 "The Hawata Extension to the Rahad Project, Part III- Engineering" Sir M. Mac Donald & Partners, Hunting Technical Services Limited, October 1966)

(ii) Tambul Pilot Study for Long Furrow to Rahad Project in 1971.

The three reports will be named and mention in this study as: design review Report, Report No.5 Hawata Extension, and Tambul Report; respectively.

The Rationale to revise and use this study of Rahad to be applied in GIS is as follows:

- The two schemes are located within the Sudan Central Clay Plain, almost extended to same latitude, separated by the Blue Nile (Fig3), with comparable climatic conditions, similar topography (gentle slope), and identical soil properties.
- Climatic Data used in Review report is mainly for Wad-Medani data
- The Gezira scheme principles and basics for design is used in the design of Rahad scheme(forerunner scheme)

Basically the used relationship ($Q=CA^{2/3}$) is for the cultivated area under basin irrigation and assumes considerable storage of potential runoff on the fields and some storage in fallow areas. The capacity of the designed drainage system for the north area can drain 10% runoff from a 100 mm storm on 10,000 fed in six days. In the south of the area the channels will drain 18% of a similar storm in six days (Sir M. MacDonald *design review Report*, 1977). However, the potential runoff from furrow irrigation is likely to be greater since the furrows will facilitate runoff from the fields. It is necessary and essential therefore to revise the design formula mentioned above; several alternative approaches are introduced by the *design review Report* as:

(1) The drainage capacity may be designed to remove the potential runoff for a design frequency (say 1 in 5 years) thus reducing ponding on the fields to a minimum. However, this is likely to prove uneconomic both in terms of the drainage capacity required and capacity of downstream structures (bridges, culverts etc.)

(2) Alternatives could be made to accept a certain amount of ponding in the fields that would not affect the crop or damage properties, and would reduce the drains size.

(3) The *design review Report* is referred to a report produced for Tambul Pilot Study for long furrow irrigation for Rahad Project (Tambul is a town in North Rahad Scheme – within the Gezira State) attempted to adopt the drainage design formula, $Q = CA^{2/3}$, to allow for increased runoff from irrigation areas using straight furrow system. A number of changes were introduced. Firstly, ponding within the cultivated area was reduced to 48 hours. Secondly, the surface runoff from a small area was assumed to be about 88 mm from a design point rainfall value of 100 mm. Thirdly, the area rainfall reduction factor was increased from 0.667 to 0.9 for areas between 500 and 5000 fed, and 0.8 for Northern Area and 0.86 for the Southern Area for areas between 5000 and 20000 fed. (Sir M. Mac Donald, *design review Report* 1977).

Comparison between the drainage rates derived from *Tambul Report* and Report No.5 Hawata Extension to Rahad Project is shown in table 5 below.

Table 5. Drainage Rates Obtained from Previous Reports (in m^3/sec.)

Item	Drainage Area (fed)	Tambul Report		Report No.5 – Hawata Extension	
		North of Jebel el Fau	South of Jebel el Fau	North of Jebel el Fau	South of Jebel el Fau
1	1	0.002	0.002	0.0017	0.003
2	100	0.20	0.20	0.04	0.067
3	1000	1.00	1.00	0.17	0.31
4	5000	4.30	4.30	0.52	0.94
5	10000	3.20	5.50	0.81	1.46
6	50000	11.50	22.0	2.31	4.17
7	100000	20.0	40.0	3.83	6.67

Source: (Rahad Project Design Review Report, Sir Mac Donald, 1977).

The design Review Report carry out a series of revision, checks, and comparison to the findings of the two reports to obtain a revised drainage rates and that includes:

a) *Point Rainfall Analysis* for rainfall in the Rahad Project Area using average monthly distribution for Wad Medani and Gedaref (1941-1970).

b) *Area Rainfall* to reduce the design point rainfall values (area reduction curves) it was concluded that a fair estimate to use and select W.M.O 30 minutes duration curve.

c) *Design Flow with Field Storage*

The design flow may be calculated using a simple water balance equation

Q_o = RF – SMD – ET (mm), where: Q_o = design flow in mm, RF = rainfall, SMD = Soil moisture deficit, ET = evapotranspiration

The calculated design flow was carried with assumption of 24 hours and 48 hours duration under the following estimates:

Open water evaporation of the order 6mm/day for the month of August (would be applicable because surplus water would be ponded on the surface as the low infiltration capacity of the clay soils once they had been wetted.

- 10 mm soil moisture deficit (only small SMD is to be expected because August is generally the wettest month.; and the results of calculations are incorporated for comparison (results are not included in this paper).

d) *Design Flows with no Filed Storage*

This is made if no allowance for surface ponding using Unit Hydrograph (peaked hydrograph), the report uses the triangular hydrograph following the procedure laid down by the Soil Conservation Services, and design peak flows.

Eventually the design review report for Rahad made a comparison of results and plot curves relating design peak flows to catchment area based on the followings:

(i) Report No. 5 Hawata Extension; **(ii)** Tambul Pilot Study;
(iii) Field Storage of 24 hours duration;
(iv) Field Storage of 48 hours duration; and **(v)** Discharge hydrograph estimates.

The plotted curves relating design peak flows to catchment area are shown in fig4

A recent Comparison from Rahad irrigation scheme rehabilitation program showed that the drainage system of the Rahad scheme is the best in the irrigated subsector.(YAM-CDC,2015)

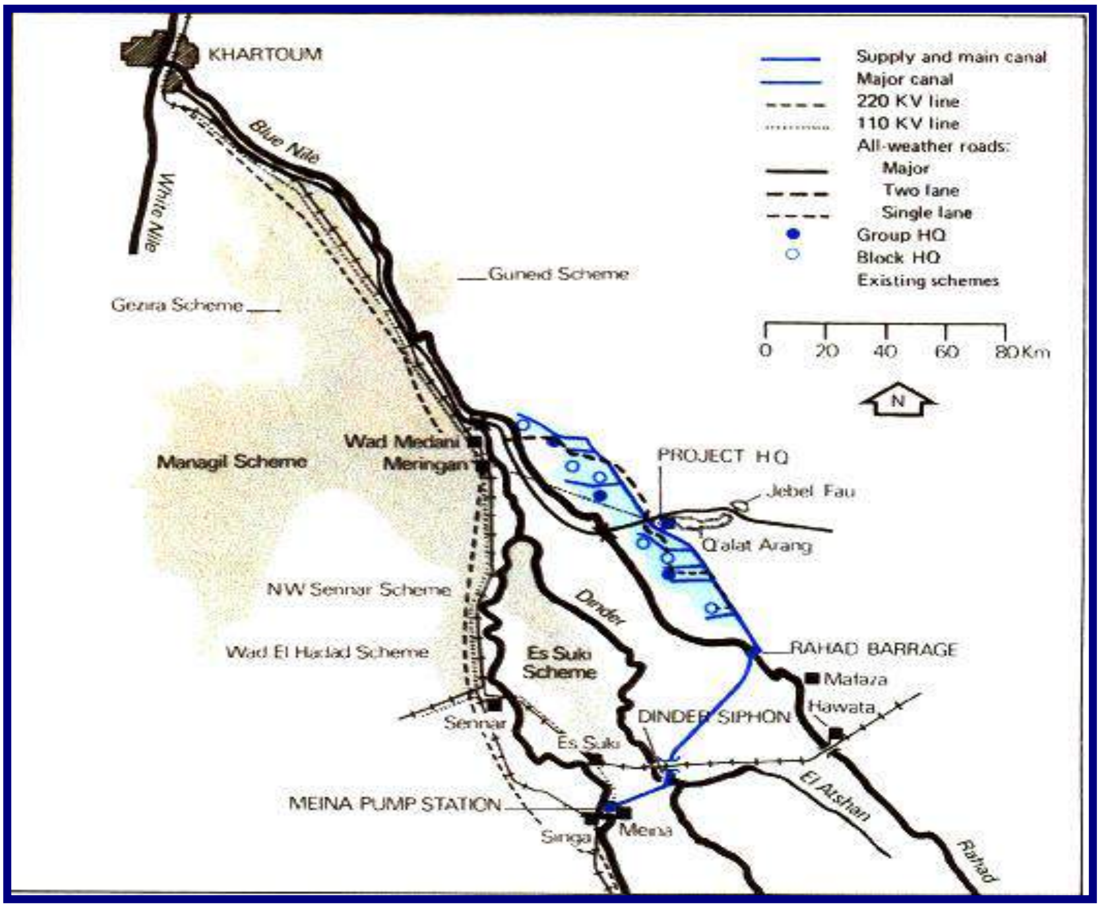

Figure3. Rahad scheme location map- source: moi annual report 1981

Experimental Site layout (Study Area)

Study Area

The selected area of the study is Bashkar collective drain, located in Tayba Block in the centre of the Gezira Scheme and starting at the end of Ibrahim canal opposite to K 110 Gezira Main Canal (nearby Beika group of regulators k108) (Messelamia Sub-division North-west Wad-Medani by about 15km), refer to figure3.

Basic data of the collective drain is as follows:

- The drain was constructed with the Scheme in 1920's
- Remodeled in 1932; length 12.1 Km, and outfall in Gezira main canal k121(*drawing Longitudinal section No.G.C.S. 32 -9076- Project directorate- MOI*).
- The drain has three reaches with parameters as follows:

1st reach, drainage area: 1800 F, Q=0.27 m^3/s, Bed width 2.0 m, slope20 cm/k
2nd reach " " : 3120 F, Q=0.40 m^3/s, " " 3.0 m, slope 11 cm/k
3rd reach " " : 5880 F, Q=0.55 m^3/s, " " 4.0 m, slope 11 cm/k.

Technical Checks

Applying the formula used for design of the system (MOI- Design Sheet File (DSF), & technical notes: we get the followings:

$Q = CA^{2/3}$ m^{3}/day, C= runoff factor, is 150 for north, and270 for south Gezira (DSF)

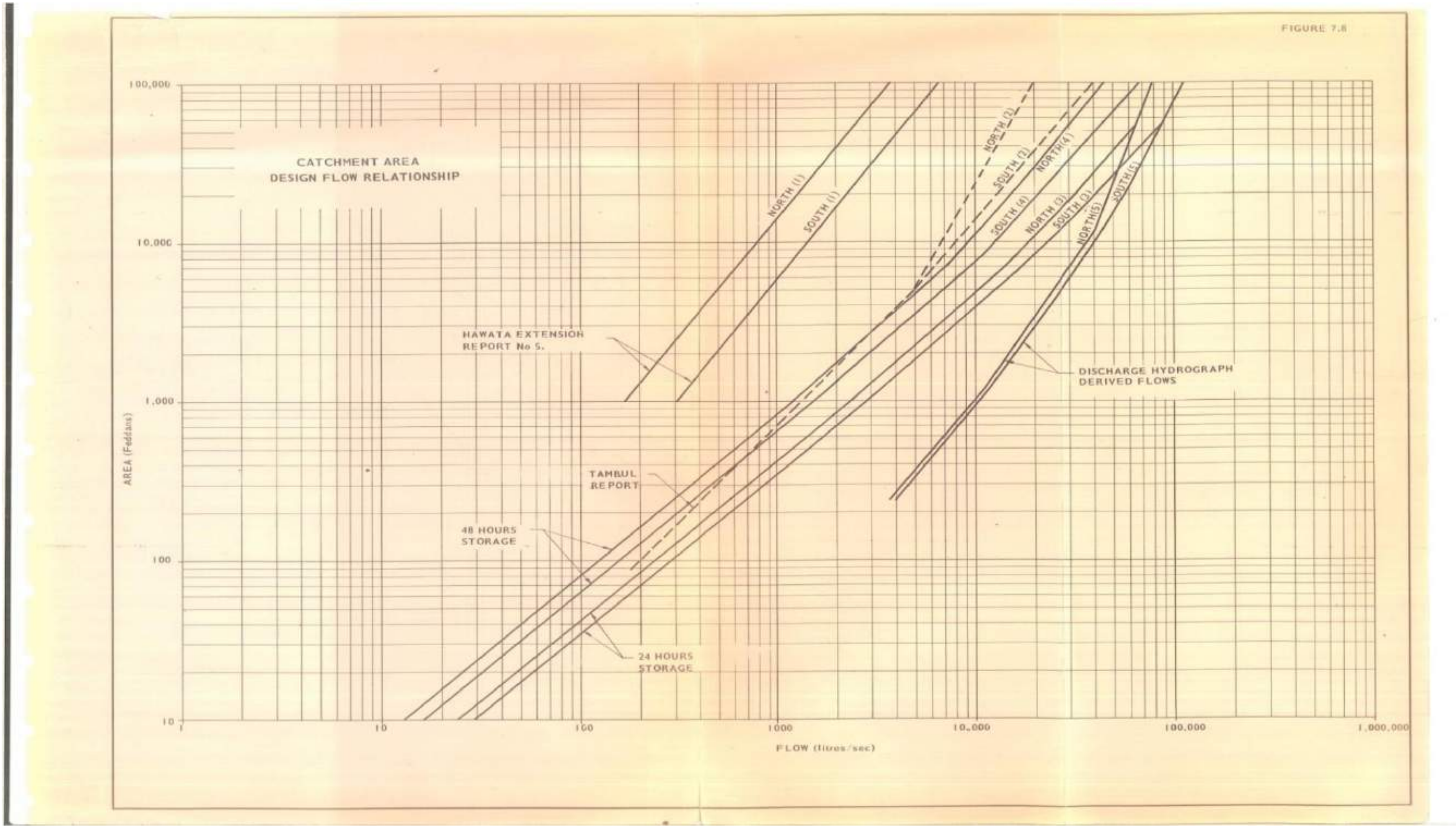

Figure 4. Curves relating design peak flows to catchment area (source: design review report,1977)

Then $Q = 150\ A^{2/3}$, A = catchment area in fed
Reach 1 → $Q_1 = 150x(1800)^{2/3} = 22{,}251\ m^3/day = 0.26\ m^3/s$.
Reach 2 → $Q_2 = 150x(3120)^{2/3} = 32{,}114\ m^3/day = 0.37\ m^3/s$.
Reach 3 → $Q_3 = 150x(5880)^{2/3} = 49{,}007\ m^3/day = 0.57\ m^3/s$.,
The check shows that discharges are compatible with the design in accordance to the formula. From the preliminary investigation the drain is infested with sediment and weeds. Bashkar collective drain outfall structure (siphon 2lines with 0.76 m size) was constructed in1932, and still in good condition, but the gates spindles are removed. Also it was noticed that the operation level during the past periods was changed.

Results and Discussion

From the investigated & revised relationship and curves relating design peak flows (Figure 4), to use and apply these relationships to Gezira drainage system, the following could be raised:

- The area of study is in the mid part of Gezira and compatible with the classification (latitude and climatic condition) of the review report study, to be in North of Jebel El Fau (refer to Figure3).
- Hawata extension report No.5 findings are based on the DSF formula under which the GIS was designed (it is identical to the original design of our area of study) and so it will not be used in our analysis.
- The criteria of no storage (hydrograph flow) have been considered in the analysis.

The result of new setting for Bashkar collective drain using the derived capacities relationships is as shown in Figugre.5, and table.6, below

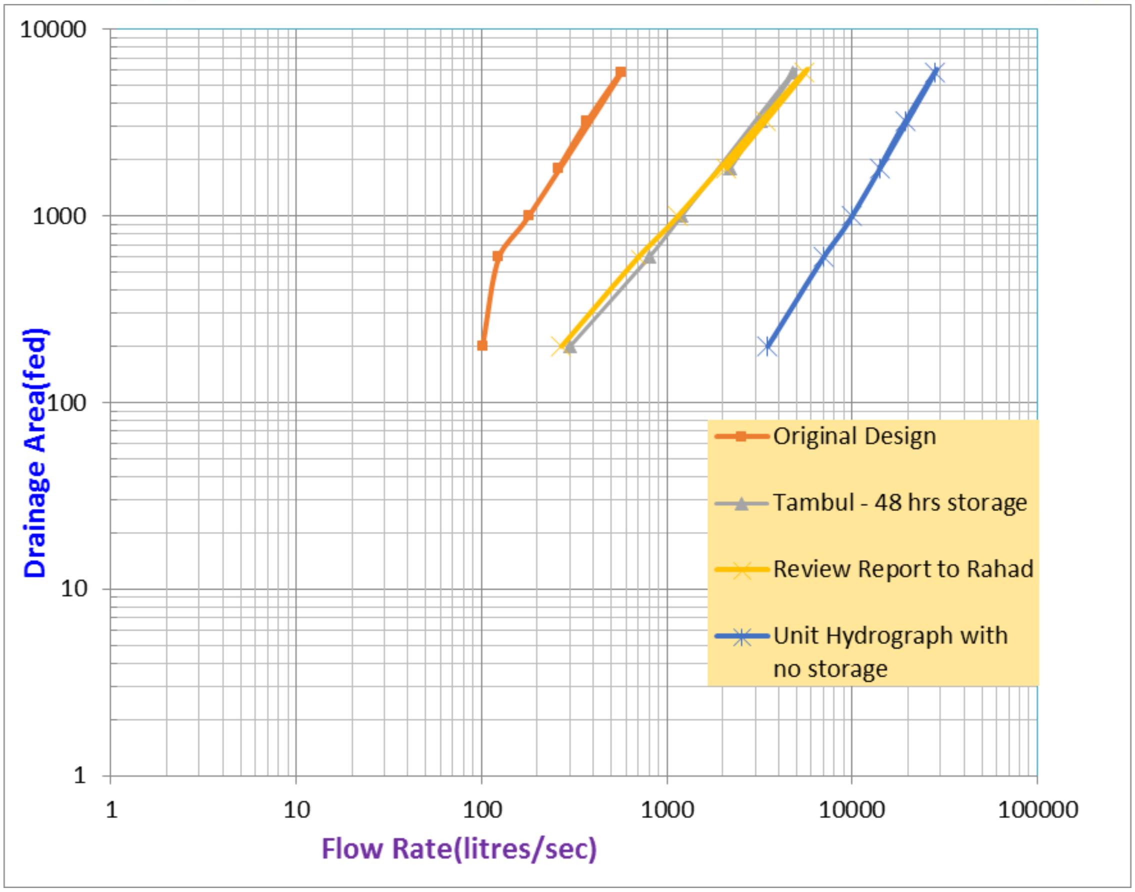

Figure. 5. Derived Drainage Capacities for Bashkar Collective Drain

Table 6. Capacities Derived for Bashkar collective drain

Item	collective drain reach	Drainage area (fed)	Drainage Capacity (m^3/s)			
			Existing Original design	Tambul Report(48 hrs storage	Review Report to Rahad	Hydrograph flow(with no storage)
1	Reach 1	200	0.101	0.30	0.27	3.50
2		600	0.124	0.80	0.70	7.0
3		1000	0.18	1.20	1.15	10.0
4		1800	0.26	2.2	2.1	14.0
5	Reach 2	3120	0.37	3.2	3.4	19.3
6	Reach 3	5880	0.57	4.8	5.5	28.0

Using the derived capacities from table6 above the design section parameters of Bashkar collective drain new setting are shown in table7, below (using Manning Formula with parameters as stated in the DSF).

Table 7. Bashkar Collective Drain New Setting Design Parameters

Description	First Reach				2nd reach				3rd reach			
	Q	Bed width	water depth	Velocity	Q	Bed width	water depth	Velocity	Q	Bed width	water depth	Velocity
	m^3/s	m	m	m/s	m^3/s	m	m	m/s	m^3/s	m	m	m/s
Drainage Area(fed)	1800 fed				3120 fed				5880 fed			
Drain Bed Slope	20 cm/km				11 cm/km				11 cm/km			
Existing Design Parameter	0.26	2	0.38	0.28	0.37	3	0.46	0.24	0.57	4	0.49	0.26
Tambal Report- 48 hrs Storage	2.2	3	1.06	0.51	3.2	4	1.34	0.45	4.7	4	1.67	0.5
Design Review Report- 48-hrs Storage	2.1	3	1.03	0.5	3.4	4	1.39	0.45	5.5	4	1.82	0.52
Hydrograph Derive Flows	14.0	6	2.13	0.81	19.4	10	2.32	0.68	27.5	12	2.57	0.73

Conclusion

✓ From the results of application of derived capacities for the selected study area, the following have been revealed:

a) The Hydrograph derived flow(with no storage), is unsuitable to be used for its high values of flow rate, which implies higher design parameters(bed widths - reaches 12m); and difficulties to be implemented for an existing system(no enough room or space, difficulties with existing structures to pass these discharges), and the high cost expected from such a change.

b) Despite some discrepancies mentioned in the Review Report about the flow rates derived from Tambul Pilot Study, we propose to use the Tambul Report with 48 hours storage derived values as it is:
   i. Higher discharges are less than those derived by the Design Review Report.
   ii. More suitable applied study to the existing Gezira drainage system which facing difficulties with spacing in its route for widening its sections, amending its structures.
   iii. Valuable 48 hours storage is of high import to the existing drainage system and can be linked with the scheme cropping pattern

- ✓ For minor drains the setting will be as originally designed with the old formula for the following reasons:
  - It's difficult to apply the new derived relationship as the minor drains now are not exist, and the space left between the end A/XX and the street and the next adjacent minor canal is short and the spoil sediment cover part of that space.
  - The cost will be high, it will be a new excavation, removing of spoil in(i) (if any) is an extra tedious and costly job.
  - Intension in this stage to recover the design system.
- ✓ For depressions where collective drains are outfalls; need to be cleaned from debris, silt, weeds, and equipped with new pumps. And where township are exist a new outfall system to be investigated (some collective drains are outfall in the main canals, e.g. Bashkar drain)

Recommendations

The applicability of the recommended revised and derived drain capacity from the Tambul Pilot Study is *not* an easy job, and after weighting up all the assumptions, revisions, and calculations which have been made, that the collective drain capacities should be calculated based on field storage of 48 hours and a constant surface runoff, and the following will be workable guidance for implementation of the study:

- Remodeling of drainage system using the new flow rates (changing as far as possible only for water depths, and minor changes to bed widths in accordance to collective drains routes).
- Changing of cropping pattern system to the 4 course rotation as it will be compatible to the design characteristic of the scheme and suitable to storage system during rainy seasons.
- The design criteria for minor drains will be as specified in the DSF, with extra amendments as follows
  - For minor drains with length less than 2 km the drain will be excavated with A/XX ditcher as small ditch with one bank, and one crossing at outfall to the collective drain.
  - For minor drains with length more than 2 km the drain will be excavated with A/XX ditcher to first 2.0 km and the remaining as parameter provided from the design, and with one bank., crossing should be in accordance to actual needs(farmers access).
  - In both above cases where the space is covered by the spoil from de-silting, it should be removed to the original ground surface and continue accordingly.
- A further study is needed for amending the outfalls of collective drains (depressions), outfalls to main canals, and rivers (Blue or White Niles) in accordance to the existing situation of each case and changes happened during the past periods.

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OPERATION AND MANAGEMENT PRACTICES OF DRAINAGE AGRICULTURE UNDER THE LOWLAND AREAS IN INDONESIA

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Abstract

Drainage agricultural development and management in Indonesia has recently been conducted by the government since 1960s. This was implemented by means of reclaiming the lowland areas with open drainage facilities for achieving several objectives among others such as the increasing of the national production of rice as a staple diet of the people, with some scattered coconut and palm oil plantation interspaced. Initially this effort was geared toward supporting the achievement and sustaining food self sufficiency, apart from providing agricultural land for involuntary transmigration population resettlement in order to support the Government Program, as well as resolving the vast decreasing of conventional irrigated agricultural lands due to the fast population explosion followed by the rapid land conversion from well developed irrigation areas to urban, industrial and other purposes.

Out of the total 162.4 million ha of potential agricultural land in the f Indonesian Archipelago, about 20.56% consists of lowland areas (tidal and inland areas) and are extended along the eastern coast of Sumatra, West, South and Central Kalimantan, Sulawesi and Papua are major islands with a total area of about 33.393 million ha of which 60% consists of tidal lowlands (about 20.096 million ha) and about 40% are the inland non tidal area (about 13.6 million ha), most of which are lowland schemes that are currently in the second development stage. The subsequently developed open drainage schemes are therefore currently demanding for sustainable operation and maintenance techniques.

This paper intends to discuss the problems, constraints and future prospects of agricultural drainage development and management with a special focus on operations and maintenance practices under the lowland conditions in Indonesia towards a sustainable future development and management. Special attention has been given to underlying experiences considering the lessons learnt from field practices for effective utilization of lowland development and management. Finally, the analysis also reviews the technical, institutional, organizational, and other nontechnical impacts as well as the impacts of climate change on low land development.

KEY WORDS: Operation and maintenance practices, Agricultural drainage, Inland lowland areas, Food crops, Soil and water management, Climate change.

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Introduction

Development and management of agricultural drainage in Indonesia has only been implemented jn the lowland areas by the government since 1960s, of which are mostly under the open drainage system. These efforts were conducted with special concentration on several objectives among others are to increase the national food production for food security program, which are mainly rice as the staple diet of the people, in order to achieve self sufficiency; to provide agricultural lands for involuntary transmigration settlement for achieving homogeneous population density of the densely populated areas on Java and the leased densely populated Outer Islands by means of agricultural drainage Government for Supporting the livelihood of the people under the involuntary Transmigration Program; to support regional development program; to increase the income per capita; and in particular to back up the increasing limited capacity of conventional irrigation development and management that has been increasingly competing with the rapid acceleration of increase of the country's population and demands for supporting the livelihood on the people in particular and the country's economy in general.

During the initial period, the development of agricultural drainage has been carried out as a gradually long term process with low cost technology under the open drainage sistem, known as the step wise development strategy. This strategy was based on the country's condition that has been facing number of problems and constraints, (Soesanto Soedibyo, 1977). These among others are: (1) Limited availability of budget for infrastructural development, and the underlying demand for developing the large areas on the Outer Island; (2) Lacking of knowledge, skill and experiences in drainage land development and management especially in the form of appropriate technical design and implementation criteria; (3) The underlying social cultural problems and constraints of the involuntary transmigration people where most of them are coming from 'dry' upland areas that are mostly unfamiliar with drainage agriculture under the lowland conditions.

At present, out of 162.4 million ha of potential agricultural land in Indonesia, about 20.56% consisted of lowland areas, and the rest of 79.44% consisted of upland. The lowland areas are extended along the eastern coast of Sumatra, Kalimantan, Sulawesi and Papua at the total area of about 33.393 million ha of which 60% consisted of tidal lowlands at about 20.096 million ha and about 40% of inland non tidal area at about 13.26 million ha, most of which lowland schemes are in the second development stage (see Table 1. List of present lowland development in Indonesia, and Figure 1., General map of the distribution area of lowland in Indonesia).

On the one hand, the majority of lowland schemes are not yet well developed, where on the other hand their potentials might be considered as an important alternative means to increase food production, to realize crop diversification and the development of the lowland area perse'. Now, the question remains on the anticipation for future lowland development, and therefore by considering the field experiences in lowland development and underlying economic conditions of Indonesia in general, it is apparent that a better utilization of the lowland resources would be highly possible, for example through application of appropriate water management system, instead of a simple open drainage systems by means of trial and error or to skip some preliminary steps of the development, with special scrutiny on the environmental impacts of the development and management in terms of technical and non-technical aspects.

Table 1. List of lowland distribution and development status in Indonesia

Location	Total lowlands potential areas			Total developed lowlands		
	Tidal lowland (ha)	Inland lowland (ha)	Total lowland area (ha)	Tidal lowland (ha)	Inland lowland (ha)	Total lowland area (ha)
Sumatra	6,604,000	2,766,000	9,370,000	615,250	279,480	849,730
Kalimantan	8,226,900	3,580,500	11,707,400	219,950	192,190	412,140
Sulawesi	1,148,950	644,500	1,793,450	85,320	36,280	121,600
Papua	4,216,950	6,305,770	10,522,720	-	25,200	25,200
Total	20,096,800	13,296,770	33,393,570	920,520	533,150	1,453,670

Source: Research Institute for Water Resources, Bandung, 2013

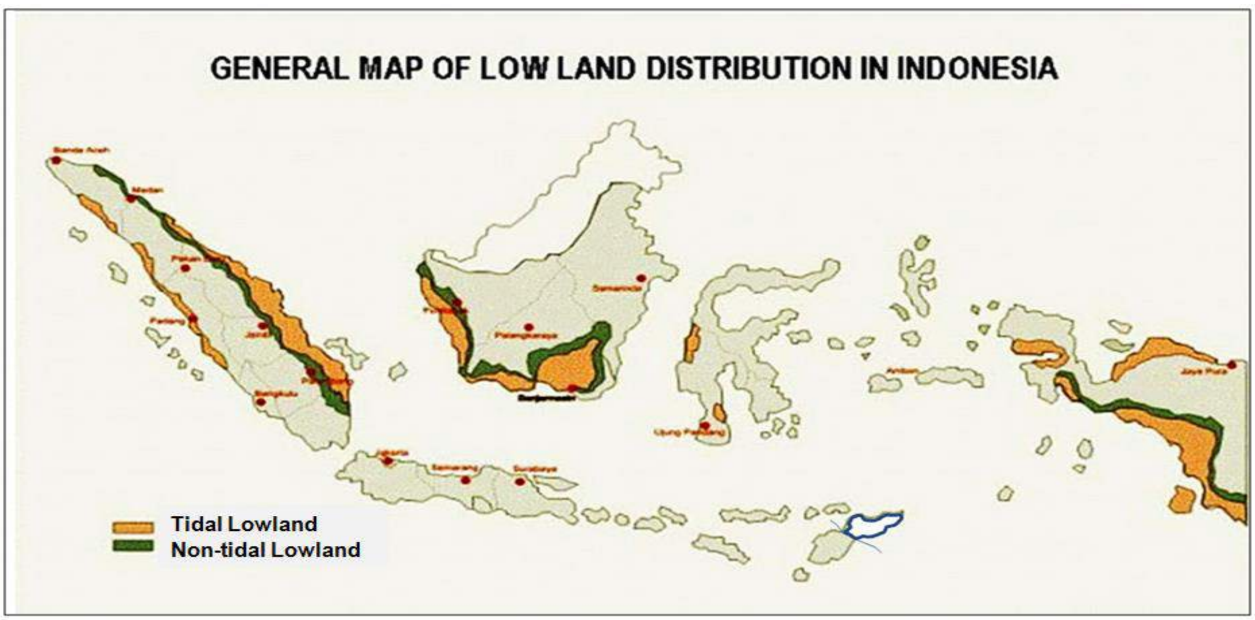

Figure 1. General map of the lowland distribution areas in Indonesia

Despite the difficulty for initial development process, lowland in Indonesia, including inland and tidal lowlands are considered to be very high potential natural resources which are scattered over the archipelago such as illustrated in Figure 1. The overall figure of the lowlands areas are currently estimated at about 33.4 million ha which is consisted of tidal lowlands at about 20 million ha and the rest are inland lowland and swamps. Most of the potential areas are located on Sumatra, Kalimantan and West Papua Islands. With the escalating demands for food as well as land demands for human settlement and industries, it is quite obvious that the appropriate lowlands development would contribute significantly to meet the increasing food demands.

Status of lowland development

Lowland Areas: From Table 1 we can see the lowland figures as previously stated above, that the total land areas in Indonesia is currently recorded at ±33.4 million ha, consisted of tidal lowlands at about ±20.1 million ha and inland lowlands at about ±13.3 million ha, scattered over the islands of: (1) Sumatra at about 10.87 million ha; (2) Kalimantan at about 10.56 million ha; (3) Sulawesi at about 1.45 million ha; and (4) Papua at about 10.52 million ha. This figure can be seen in the following schematic diagram stated in Figure 2 as follows.

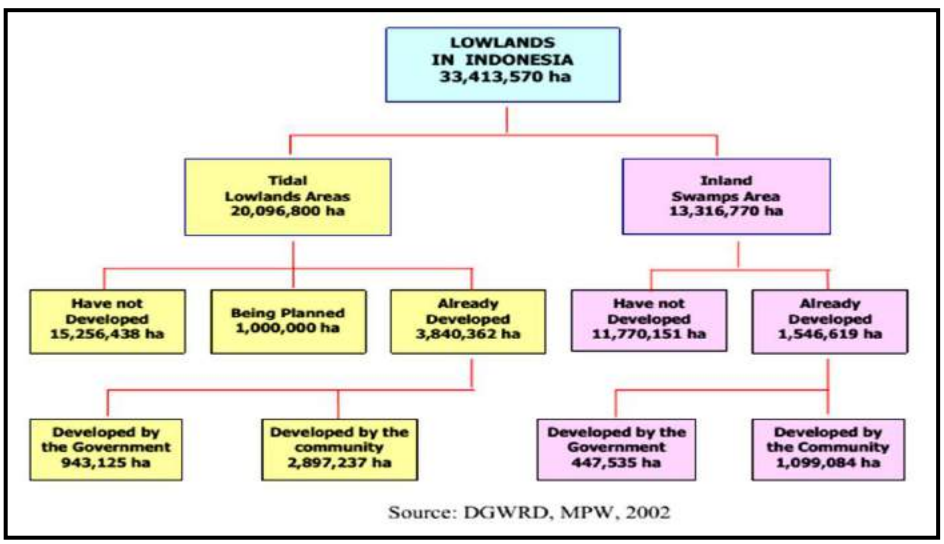

Figure 2. Schematic diagram of lowland development and potential in Indonesia, including tidal lowlands and inland lowland areas

Tidal lowland areas

Tidal lowlands are the lowland area near the coastal vicinity that is affected by tidal movement of the river level as the result of tidal fluctuation of the sea. According to hydro-topography the tidal lowlands are divided into four categories (see Figure 3 below):

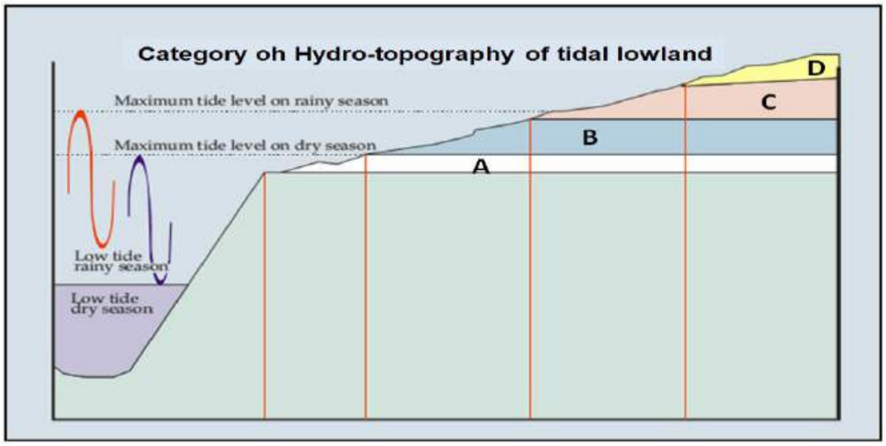

Figure 3. Category of hydro-topoghraphy of tidal lowland

Category A: The lowlands areas that are frequently inundated by high tide due to fluctuations of water level at the river. This type of land is highly suitable for cultivating lowland paddies.

Category B: The lowland area that are occasionally inundated by high tide due to fluctuations of water at the river. This type of land is suitable for mono-crop lowland paddy cultivation during the rainy season and second crops during the dry season.

Category C: The lowland areas that have never been inundated by the highest tide due to fluctuations of surface water of the river, however, the tides are still having effects on the fluctuations of ground water up to 50 cm below top soil surface. This type of land is suitable for annual paddy crop during the rainy season and second (upland) crops during the dry season.

Category D: The lowland areas that have never been inundated by the highest tide due to fluctuations of surface water of the river and having ground water surface deeper than 50 cm from top soil surface. This type of land is suitable for upland crops and perennial plantations.

Inland lowland area

Inland lowland also known as swamp land is the type of lowland that is not affected by tidal fluctuations. This type of low land is divided into three hydro-topographical zones namely: (1) The *"lebak pematang"* zone, which is the shallow dyke with short term inundating period; (2)

The *"lebak pertengahan"* zone, which is relatively deep and with longer period of inundation; (3) The *"lebak dalam"*zone, which is deeper than the other categories, yet with longer inundation period or permanently inundated.

In general, the inland swamp developments are prioritized on the *"lebak pematang"* and "*lebak tengahan"* zones, while the *"lebak dalam"* zone is kept preserved under its natural condition. Please see the inland lowland category as illustrated in the following figure.

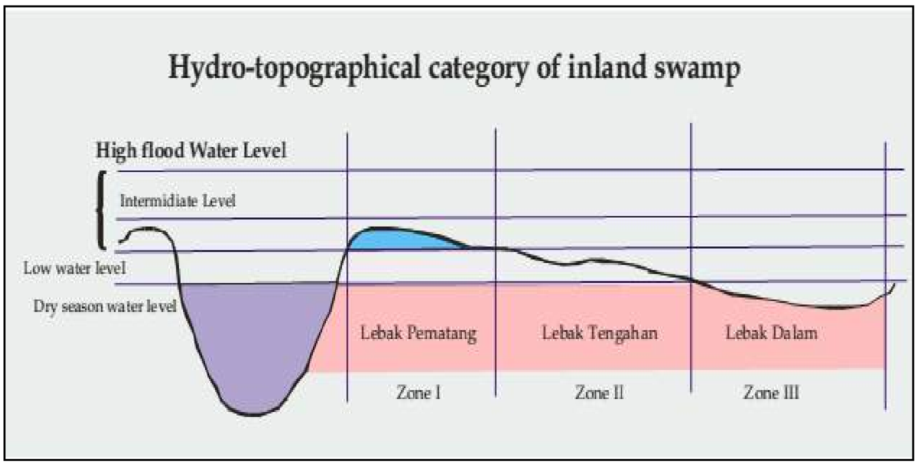

Figure 4. Hydro-topographical category of inland lowland

Based on the empirical practices, one of the determinant factors for a successful lowland development is the appropriateness of land preparation technique together with effective water management in such a way to be able to maintain the optimum plant growth. Given the vulnerability nature of the lowlands, the development must be conducted judiciously and gradually by carefully considering both technical and non-technical aspects such as socio-economic as well as environment. Based on long terms practices the lowland development phase is mostly consisted of three stages of development process. These stages should therefore be considered carefully for post construction operation, maintenance and management.

Stage I: Initial land reclamation process which is conducted by constructing a series of simple hydraulic infrastructures, such as open channel drainages with regulatory structures. At this stage, the water management is merely dependent upon the natural condition.

Stage II: Follow-up development as the continuation of Stage I which was conducted by means of improvement and upgrading of the existing drainage infrastructures. The existing water channels usually equipped with regulatory structures and levees for flood control and flood prevention. In this stage, it is important to guarantee the reasonable level of fresh water circulation by separating the conveyance water supply and drainage conveyance.

Stage III: Efficient utilization of the available lowland and water resources by means of fully operating and maintaining the developed infrastructures. Under this development stage, the water and land management are already stabilized with independent and sustainable operation.

Low-cost development approach

Since the underlying condition of agricultural development is still dominated by gravity irrigation, then at the initial stage the lowland development is still put at the second priority by adapting the low-cost development approach by which the newly reclaimed land can only be developed marginally and the marketable production surpluses will be expected to be materialized at the subsequent stage later on. Therefore the lower return per ha will require larger land holding to generate reasonable incomes, for which the land holdings allotted to new settlers, should not be less than 2.00 ha per household.

Besides budgetary advantages, low-cost development also offers some attractive advantages in future absorption capacity of the projects, while the soil productivity can still be increased in the future whenever funds are available for further investment. With this in mind, the area to be developed still have the capacity to absorb the livelihood improvement of the future generation of famers in the particular area.

Operation of canal and hydraulic infrastructures

Objectives of appropriate water management at lowland area: Implementation of water management at the drainage agricultural under the lowland area should consider the following objectives: (a) Achievement of proper soil condition for agricultural implementation (proper land maturity, acidity and elimination of hazardous materials) and water quality that could support agricultural practices; (b) Fulfillment of water supply and drainage to meet proper plant growth; (c) Elusion of over drainage that could entail formation of acidity, toxic materials and excessive land subsidence, particularly for peat soil; (d) Fulfillment of proper balance on water demand for plant growth and daily life water consumption; (e) Elusion of saline water from disruption to plant growth and other water use beneficiaries; (f) Achievement of navigation control (if required); and/or (g) Protection of canal embankment from soil erosion and land sliding.

Water management zoning: Determination of planning and canal operation must be based upon Water Management Zoning (WMZ) which is unit of land use that combined with quality of physical characteristic of land and type of the proposed utilization of land. Determination of this WMZ is very important because it would bring about consequences on the types or form of water management that must be planned including selection of type of water management infrastructure and operation procedure. WMZ is highly related with land use planning and arrangement of water infrastructures. Some particular areas have the similar demand for water management based on the physical characteristic of the land in terms of hydro-topographical type, drain ability and type of soil. Factors that are affecting similarity of land for WMZ are among others are: depth of tidal irrigation, drainage capacity of land, depth of pyrite layer, depth of peat soil, salt intrusion, and types of land units. Consideration of WMZ in water management planning would result in the proper management system.

Traditional system (Type 1): This is the oldest system, applied by *Banjarese*, *Buginese* and *Malays* traditional farmers they reclaimed the lowland areas by connecting them with a tidal river. During low tides, they are connecting canal drains the (toxic) water to the river, while during high tides fresh water enters the canal system and can be conveyed to the fields. Under this system, each canal serves about 40 ha agricultural land, so only a fringe of few km along the river can be developed by this system. The distance between two canals is about 400 m. This scheme has been widely implemented in Sumatra and Kalimantan Islands.

***Anjir* system (Type 2):** In South and Central Kalimantan, main canals were constructed within the period of 1950 to 1970s. These canals were constructed between two tidal rivers, to allow for inland navigation. These navigation canals were incorporated with other lowland reclamation projects and also serve as transportation for the neighboring drainage lowland areas. Operation and management for this type of system should pay special attention on sedimentation problems due to the tides at both ends have more or less the same phase. In most cases, sedimentations are coming from the canal bank erosion due to navigation activities.

Rib system (Type 3): This system is mainly applied in Sumatra and it can be characterized by its right-angled layout (Sugandar, 1976). The principle of this system is that areas are made suitable for agriculture at low costs by making maximum use of tidal fluctuations in the canals. The system mostly composes of main canals which are used for navigation, secondary canals and tertiary canals. These water management systems are more flexible for adaptation.

Fork system (Type 4): This open drainage system was introduced to overcome acidity problems, in Southern Kalimantan for reclamation of potential acid sulphate soils (Soenarjo, 1977 and Harjosopangarso, 1986). The system consists of a primary canal of approximately 2,000 m in length and it branches into two or three secondary canals with length in the range of 3,000 to 10,000 m. Tertiary canals are constructed perpendicular to the secondary canals with the lengths of 2,000 m. The primary and secondary canals have also navigation functions. Most of the systems have a large pond (a so called *kolam*) at the end of each secondary canal with the dimension of 200 x 200 m. In fact the dimension of the *kolam* is too small in order to have the jet flow effect for flushing the systems.

Combined system (Type 5): In addition to the above four systems, a combination of the rib and fork system has been applied as well.

For more details the general elaboration of the types canal layout of hydraulic infrastructures can be seen at Figure 5., below.

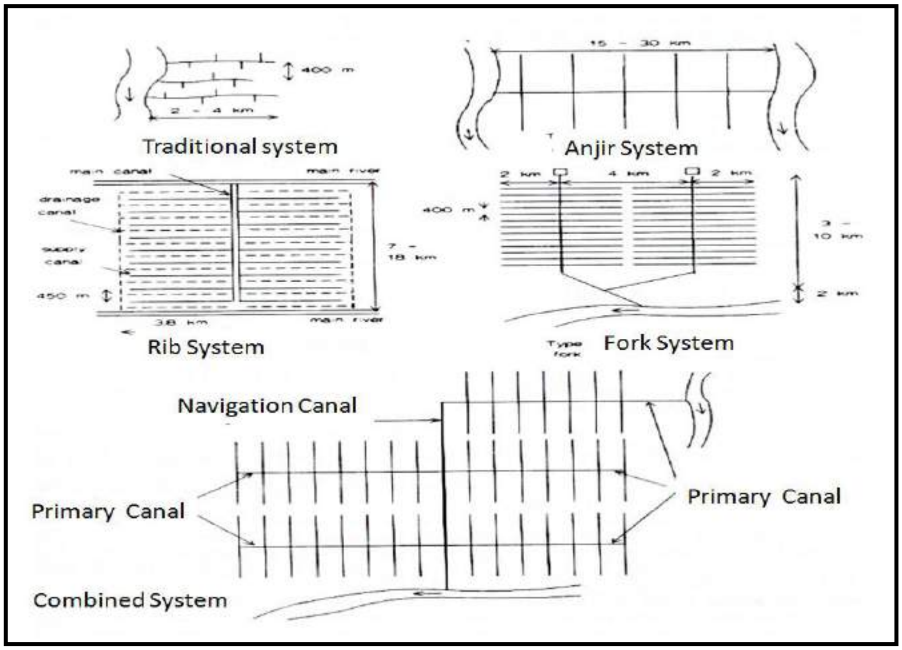

Figure 5. General layout of canal system and hydraulic infrastructures of tidal drainage agriculture (traditional, *anjir*, rib, fork, and combined systems)

Land suitability and water management practice

As the starting point of land suitability analysis, hydro-topographical conditions in the tidal lowlands are defined as the field elevation in comparison to river, or canal water levels in the nearest open water system (Suryadi, 1996). In this context, four hydro-topographic classes are generally distinguished: (1) Category A (tidal drainage agricultural areas). The fields can be flooded by the tides at least 4 or 5 times during a 14-day neap-spring tidal cycle in both the wet and the dry season. These areas are situated mostly close to river mouths; (2) Category B (periodically tidal drainage agricultural areas). The fields can be flooded by the tides at least 4 or 5 times during a 14-day neap-spring tidal cycle in the wet season only; (3) Category C (areas just above tidal high water). The fields cannot be regularly flooded during high tide. The groundwater table may still be influenced by the tides – than it requires drainage agricultural system. Cropping is mainly dependent on rainfall, although some additional water supply by infiltration might be possible with an intensive field ditch system. Many category C areas in the wet season are planted with rice crop. For the dry season dry food crop is the most likely alternative. With a sufficiently large tidal range the cultivation of tree crops is an option for these areas; (4) Category D (upland areas). The fields are entirely above tidal influence. Dry food crops and tree crops are best suited to these areas when they do not receive extra water from adjoining higher areas.

In the relatively low tidal lowland areas (category A and B) the main purpose of the water management system is to control drainage by operating the water control structures based on the water requirement in each cropping stage. If required water can be supplied during dry periods. From time to time flushing may be required in areas where acidity still can develop. In the relatively high tidal lowland areas rice crop is completely depending on rainfall, but subsurface flow of groundwater to the adjoining secondary canals may cause relatively high water losses. Therefore the main purpose of the water management system could be to control relative high water levels in secondary canals to prevent too low groundwater tables. For water management at the drainage agriculture, the implementations are based on a number of information with spatial distribution characteristics which have to be taken into account. These among others are topography, soil, hydraulic, hydrology, cropping systems and local practices. These series of information are very important to minimize the negative impacts to sustainable development of drainage agricultural development.

Flap gates for controlling incoming and outgoing water flow

The existing hydraulic infrastructure in the already reclaimed schemes which were based on the low-cost development approach, have typical features in common. In principle, the tidal flow that affect the drainage agricultural practices are utilizing flap gates, with the function of controlling incoming and outgoing flow of tide through the dual function of the channel (some time refers to as "*irrinage"* (irrigation and drainage) canal. Thus during the ebb flow, the incoming water from downstream is protected by maintaining the stable level that maintain the moisture content at the root zone. Similarly, during the tidal flow, the outgoing flow of the water must be released to a certain extend that the moisture content of the soil will not drop below the optimum moisture content for supporting the optimum plant growth (See Figure 6. and Figure 7., Example prototype flap gates model system and the dual functioned flap gates made of hollow fiber glass – filled with water for maintaining proper balance -- installed at the outlet and inlet structures of the drainage agricultural canal that are in operation).

Water Gates for controlling outgoing water flow: For the non tidal lowland, the control gates are not dual function, in the sense that drainage water management for drainage agriculture is designed for allowing the excess water to leave the land till the moisture content is at the stable condition for supporting the underlying plant growth. Thus, the water gates are continuously operated to maintain the optimum water level set up for maintaining the underlying water use, including the excess water resulted from time to time from rainfall in each particular location of drainage agriculture.

Gate operation for water control at the macro level: For water management at the macro level, which is water control at the drainage infrastructure at scheme level prior to distribution to the micro level (farm level), water management is very crucial because it determines the availability before distribution to the micro level. The objective of water control at this macro level among others are: (a) To release the excess water at the surface as well as at the ground water level; (b) For protection and flood mitigation; (c) For protecting salt intrusion; (d) For provision, allocation and distribution of raw water for drinking water; (e) Bulk water allocation for agricultural and industrial demands; (f) Control of water elevation at the main drainage canal; (g) Water quality control at the main canal level; and (h) Controlling the water transportation.

Gate operation for water control at the micro level: Especially for the water management at the micro level which is water control at the farm level related with the daily condition and environment of plant growth, the gate operation must be properly managed in such a way to be able to meet the water management at the micro level for supporting optimum crop water evapo-transpiration, these among others are: (a) Water requirement for optimum nutrient absorption; (b) Avoidance of germination, growth and spread of plant pests and diseases; (c) Control of plant pest and diseases; (d) Avoidance of negative impacts of toxic soils; (e) Leaching of component of toxic materials; (f) Controlling of soil moisture content and ground water level at the farm block; and (g) Controlling of water quality for plant growth at the farm level.

Figure 6. Prototype model and operation principle of double functioned fiber glass flap gate (left); Figure 7. Flap gates installed at hydraulic structure for operation (right)

Problems and constraints

General problems and constraints: In general, there are a number of problems encountering operation and management of agricultural drainage in lowlands areas, these are among others: (a)

Implementation performance cannot be conducted in accordance with the main tasks and function of the responsible institution because of integrated nature; (b) Since the implementation of Local Government autonomy in 2003 the field operation and management personnel (water master, ditch tenders and gate keepers) are directly under the control of local district government, and most of them are retired, others are assigned to other local government agencies; (c) The actual trend of local farmers of transforming the agricultural practice from food crops to palm oil plantation; (d) Severely lacking of O&M as well as management budget (mostly only available between 30 to 60% of the requires budget); (e) Lacking of appropriate understanding on the principle and implementation of maintenance and rehabilitation activities; (f) The Implementation standard of implementation of O&M budget support from central government are differed from one implementing agency to others; (g) Lacking of O&M facilities for field staff; (h) Poor coordination amongst central and local government authorities on implementation of O&M activities; (i) Ineffective working condition, coordination and participation of water user association in O&M of drainage agricultural infrastructures at the farm level; (j) Poor O&M budget allocation in terms of adequacy and utilization schedule by the local government, so performance of operation and services are hardly synchronized; (k) O&M activities of drainage infrastructures between agriculture and fishery sector are hardly adjusted in terms of transplanting and fishery breeding; (l) Inappropriate role and responsibilities of the farmers for farming O&M of drainage infrastructures at the farm level.

Land resources potentials are among others: (a) Soils are mainly clays, which make them productive only after reclamation, unless they are covered by peat; (b) Rainfall amount and distribution in the wet season are adequate for one rain-fed crop; (c) If additional irrigation is introduced (low lift pumping), wetland rice will provide a high yield under the proper water management. This alternative may in future proved to be a feasible development option; (d) If drainage measures are taken, upland crop cultivation, such as cassava, maize and soybeans, will be possible. Perennial crops like coconut and oil palm may also be grown well.

Constraints of tidal lowlands are among others: (a) Tidal lowlands are located in remote areas, hindering supply of inputs and marketing of products; (b) Close to river mouth, salinity may create problems for agriculture and drinking water, especially during the dry season; (c) A substantial part of the tidal lowlands are covered by (potential) acid sulphate soils and/or peat soils. So the water management infrastructure has to be adjusted to the changing conditions; (d) Inadequate soil and water management systems in most places; (e) In many tidal lowlands, lack of supporting data, mainly related to the soil, hydro topographical and land suitability conditions. Labor shortages that favor farming technology systems without land preparation based on low yielding traditional rice varieties; (f) Lack of O&M of the water management systems at tertiary and secondary levels and almost non on-farm water management; (g) Inadequate infrastructure and post harvesting management facilities; (h) Lack of good credit facilities and agricultural inputs and limited market facilities; (i) existence of pest and diseases; and so on.

Constraint on water allocation and management: (1) The implementation of gradual approach on lowland development is mostly associated with low land reclamation technology, which is relatively new for Indonesian engineers. Therefore, and hence much experience and empirical works are needed on the basis of trial and errors; (2) Implementation of large-scale land reclamation is highly susceptible to environment; (3) Inappropriate water allocation and management would bring about significant reduction of agricultural productivity due to soil salinity; (4) The effort to separate conveyance and drainage channels usually encountered by a number of constraints among others the farmers attitudes; irregular water requirements for individual farmer; constraint of gates operation on water channels that are utilized for water transportation are regarded by the farmers as obstacle rather than solution; lacking of O&M endeavors would result in a number of problems.

Constraints on socio-economic and agro-economic aspects: Based upon experience in the past low land development implementation, much attention had been given to the technical as well as civil engineering aspects and less attention were addressed to the non technical aspects, including the lack of continuous monitoring and concern on land development, gradual process of the maturity of land consolidation. Irregular condition of soil fertility, the magnitude of soil acidity and application of fertilizer; irregular physical characteristic of lowland swamp in relation with the depth of pit soil and acid soils as the accumulation of soil acidity; the need of regular fresh water circulation for maintaining consistence soil leaching.

Environental impacts and climate change

Environmental Aspects: One of the most vulnerable aspects of lowland development to take into consideration is the impact of physical intervention on the sustainable balance of aquatic ecosystem. This is partly due to the nature of the swamp area as the marginal land for agricultural development. Therefore, any abrupt change due to development intervention such as land reclamation, would encounter the natural balance of aquatic habitat, including the natural equilibrium of pests, aquatic weed, and other such bio-environment.

Other crucial environment aspects of lowland development is about the impacts of escalating degradation of upper watershed of the river basin due to uncontrollable human activities such as traditional shifting cultivation, logging and other such activities. This aspect, therefore, needs to be scrutinized through appropriate integrated watershed management. Further to this, the lowland development must be addressed by virtue of environmentally-friendly approach, should the drainage agricultural practices in such an area to be environmentally sustainable.

Anticipation of impact of Climate Change: One of the most important aspects of O&M and management of drainage agriculture at the lowland area is anticipation and hence adaptation as well as mitigation of the impacts of climate change, which is relationship with the emission of CO2. The facts of CO2 emission at the lowland area in Indonesia that must be properly scrutinized are among others: (a) Based on the report of Wetland International and Alterra Wageningen 2006, the total lowland area in Indonesia is about 33.4 million ha, of which 22.5 million ha (67%) consisted of peat soil area, at the average of about 32% out of 22.5 million ha associated with "occupied land"; (b) Till present about 1.8 million ha has already reclaimed by the government, and about 350,000 in the form of inland lowlands and hence about 464,000 ha consisted of peat soil area (at an average assumption of 32%); (c) In this regard, there two major factors affecting the significant emission of CO2 at the peat land area which are over drained and forest fire; (d) With an estimate of surface water draw down at 10 cm due the impact of climate change and/or over drained would resulting CO2 emission at about 13 ton/ha/year (Wetland International and Alterra Wageningen 2006); (e) With an assumption of 464,000 ha of peat land that that had been suffered from drawdown of surface water at 10 cm, means that about 6 million ton of CO2 per hectare per year has been ejected to the atmosphere with the subsequent impact to human life on earth.

Lessons learnt

Based upon the long term implementation of lowland drainage agriculture in Indonesia there a number of lessons learned for future development and improvement of the reclaimed areas, new reclamations and the conservation of areas, among others are: (1) Improvements in reclaimed areas, the first priority would have to be to make better use of the developed infrastructure by a better O&M, both at the on-farm and at main system levels, using the past experiences as a guidance; (2) For new tidal drainage agriculture the areas that have a potential for reclamation have been identified, may be expected that sooner, or later the remaining potential tidal lowland areas will be reclaimed. This is still a very substantial area compared to the present total cultivated area with paddy rice in the country of about 8.5 million ha; (3) Environmental considerations and sustainability. Decision on lowland development projects for drainage agriculture has to be tightly related with the use of ecological data for all decisions on future lowland development projects. The deep peat soil areas are basically unsuitable for development on a sustainable basis and mostly are demanding for preservation; (4) First generation problems. At the initial stage there should be a strong commitment of the involved organizations. Farm sizes and layout pattern, that initially have been implemented, may become inadequate to cope with developments in society, and hence, farming may become uneconomic; Insufficient institutional arrangements and organization to properly operate and maintain the flood protection; Insufficient skill of farmers to cultivate crops under the conditions as prevailing in the newly reclaimed land; and other such lessons leant.

Based on these lessons learnt it is highly important to develop proper action plan for the medium and long term lowland drainage agriculture taking into consideration the following components: (1) Data base development, including inventory activities and seminar of lowland development in Indonesia in order to know the actual stage of development which cover physical and human resources; (2) Integration of lowland development with the regional spatial planning; (3) Effect of climate changes in lowland development in Indonesia; (4) Capacity building and human resources development related to lowland drainage agricultural development in Indonesia.

Most important lesson learnt is that the future potential of lowland drainage agriculture become more and more important for Indonesia and will be the future for agricultural development. This is particularly the case that there currently a continuous loss of agricultural lands on Java Island for urbanization, industry and other non agricultural infrastructures – the loss of agricultural land is about 30,000 to 40,000 ha/year. With the underlying trend decrease of rice production on Java Island due to continues land conversion to non-agricultural utilization; and the increasing land and water competition with the requirements for rice cultivation, the only alternative in the future for compensating the above trend is on intensifying the future potential of drainage agriculture. Next to that, a monitoring program for climate change, especially sea level rise should be done soon in order to analyze and to evaluate the possible impact of sea level rise to lowland development in Indonesia and must immediately anticipated by means of adaptation or mitigation of Climate Change as early as possible.

Future Challenges: For obtaining the maximum advantages, the future use of lowland developments for drainage agriculture are encountered by a number challenges and constraints including among others: (1) Lowland drainage agricultural development involves cross-sectoral activities, therefore it requires intensive inter-agency coordination among the relevant institutions; (2) Lowland drainage agricultural development takes relatively a long time process, which demands for long-term commitment on financial investment; (3) The facts that lowland drainage agricultural development possesses good prospect a large spectrum, therefore, development planning would be increasingly become more complex in line with the demands for sustainable and environmentally sound development; (4) The follow up stages of lowland drainage agricultural development requires adequate economic and social infrastructure supports for increasing demand of sosio-economic development; (5) The complexities associated with the prospective lowland agricultural drainage development would require more than just capable human resources but also demanding for highly qualified personnel as well as reliable R&D support; (6) In order to gain a maximum advantage of the developed lowland drainage infrastructures, effective O&M of the water resources facilities must be undertaken and improved on sustainable basis; (7) Climate change and particularly the sea level rise which is predicted as 0.65 m per century (BAPPENAS, 2004) will have an impact to the lowland conditions especially related to it hydro-topographical condition. The impact will be more areas will change from B hydro-topographical category to A and from C to B (Rahmadi, 2009). Therefore water management systems would have to be adapted to these conditions in addition to the proper monitoring system, in order to evaluate the sea level rise as early as possible.

Concluding remarks

Based upon experiences it can be concluded that lowland drainage agricultural development is a long term and dynamic process of land and water relationship. Most of the lowland drainage agricultural development schemes in Indonesia are in the second stage and for immediate future development a careful and environmentally sound scenario should be carefully taken into account. It is evident that lowland drainage agricultural development in Indonesia has already been undertaken for more than 25 years. During which, the Central Government, especially the Ministry of Public Works, D.G. of Water Resources and the Ministry of Agriculture have been involved, both in research, planning as well as implementation.

Lowland drainage agriculture in Indonesia has a future potential to become the rice granary of Indonesia. For that purpose, the first priority is to make better use of the developed infrastructures by conducting a better O&M at on-farm and at system levels. Subsequently, the farmers have to be supported consistently along the improvement of irrigation and drainage agricultural practices, crop diversification and post harvest activities. In addition it is highly important in this case, also to protect the ecological valuable areas as well and conservation of the areas that are having potential land subsidence and other hazards in the near future.

A nationwide study for lowland drainage agricultural development and management as well as conservation in Indonesia should be carried out soon in order to identify the prospects of lowlands as well as the related conservation toward sustainable environmental conditions, development stage, human resources development, potentials and also constraints for the future use for other land utilization such as for agriculture, conservation, urban, as well as adaptation and mitigation effect of climate changes.

Based on these activities, an action plan for lowland development in Indonesia for medium and long term can be derived. A monitoring program for climate change, especially sea level rise should be done soon in order to analyze and to evaluate the possible impact of sea level rise to lowland development and hence sound measures can be proposed as early as possible.

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SHALLOW GROUNDWATER DRAINAGE AND ITS WATER QUALITY FROM PROTECTED FARMING IN KOREA

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Abstract

In the agricultural watershed in Korea, nutrients are discharged through various means such as soil erosion, runoff, infiltration, or drainage. Protected farming has expanded by increasing the demand for value-added agricultural products in Korea. In some agricultural areas, particularly in protected farming, due to excessive fertilization and irrigation, the nutrient excess phenomenon is becoming increasingly serious. The drainage of water and non-point source pollution (NPS) management under the protected farming method needs to be devised to manage water quality of shallow groundwater and reduce NPS pollution loads from protected farming practices. This study was conducted to investigate shallow ground water infiltration and drainage from protected farming cultivation in comparison with conventional farming practices. In the protected farming field, tomato and cucumber crop were cultivated twice a year using a drip irrigation system and nutrients were applied by fertigation. Irrigation, soil moisture content, shallow ground water level and flow, and weather conditions were monitored and soil water and soil on protected farming sites and shallow groundwater samples at 8 different sites on the watershed were also collected during the crop growth season to investigate water drainage and nutrient leaching characteristics in protected farming. Key NPS such as electronic conductivity (EC), total phosphorus (TP), total nitrogen (TN), and nitrate-nitrogen (NO_3-N) were analyzed. The results show that NO_3-N concentration and EC of soil water is high in the total soil layer, and some nutrient concentration in the sub-soil layer is higher than those in the upper soil layer. In addition, the nutrient concentrations in shallow groundwater is generally higher as compared to conventional farming. Eventhough fertilization and irrigation were applied regularly for crop production, there is a possibility of over fertilization and it may affect nutrient accumulation due to poor drainage of subsoil whereas in case switching

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the land use from paddy fields is to protect farming or nutrient leaching when over irrigated. In addition, in areas having high shallow groundwater level, a direct impact of excessive irrigation and fertilization increased in accordance to drainage and water flow. This results will serve as the platform not only for long-term shallow groundwater water drainage and nutrient monitoring and management under the protected farming cultivation approach but also for the derivation of guidelines on farming practices enhancement to reduce NPS loads from protected cultivation.

KEY WORDS: Non-point source pollution, Protected farming, Shallow groundwater, Water drainage.

Introduction

Protected farming has been expanded due to the increasing demand for value-added agricultural products and the decreasing area of available agricultural land in Korea. Approximately 60 % of the new protected farming area has been installed in paddy fields (Lee et al., 1998). In protected framing cultivation, unlike the paddy field cultivation, precipitation is blocked and water for crops is only obtained through irrigation.

Nutrients for plant growth are supplied by fertigation which involves supplying nutrients in irrigation water for increasing nutrient uptake by plants (Mahajan and Singh, 2006; Liang et al., 2013). In addition, protected farming in Korea occurs year-round more than two rotations a year. Due to the misconception that the application of large amounts of nutrient results in high crop yields, excess nutrients are a potential source of nonpoint pollution accumulate in the soil and leach downward with the application of irrigation water, possibly causing soil and groundwater contamination (Thompson et al., 2007; Shi et al., 2009; Min et al., 2012; Hong et al., 2014).

Because of yearly increases in protected farming cultivation, nitrate-nitrogen (NO_3-N) concentrations in the shallow groundwater near the protected farming area had increased and in some cases the concentrations exceeded the groundwater quality standard for agricultural water 20 mg L^{-1} (Ha et al, 1997). If contaminated or salinized groundwater is used for irrigation water, it can cause a cycle in which nutrients reaccumulate in the soil and leach to shallow groundwater (Lee et al., 2008).

According to Hong et al. (2014), the total NO_3-N losses in protected farming practice through leaching to deeper soil were 54.7-758.6 Kg N ha^{-1} in one rotation. A significant amount of nutrients were not utilized for crop growth but instead leached in accordance with the movement of the soil water. To minimize leaching of nutrients into shallow groundwater, it is necessary to investigate the processes of shallow groundwater fluctuation and leaching. In particular, nitrogen is a mobile nutrient that is rapidly leached (Hong et al., 2014). Irrigation with high nitrogen use in protected farming results in the substantial loss of nitrogen through leaching and the consequent contamination of the shallow groundwater, especially, NO_3-N (Li et al., 2003; Thompson et al., 2007, Wan et al., 2010).

In this study, to investigate shallow groundwater drainage and its water quality from protected farming, soil moisture content, fluctuation of shallow groundwater and water quality were collected and analyzed.

Materials and methods

Study area

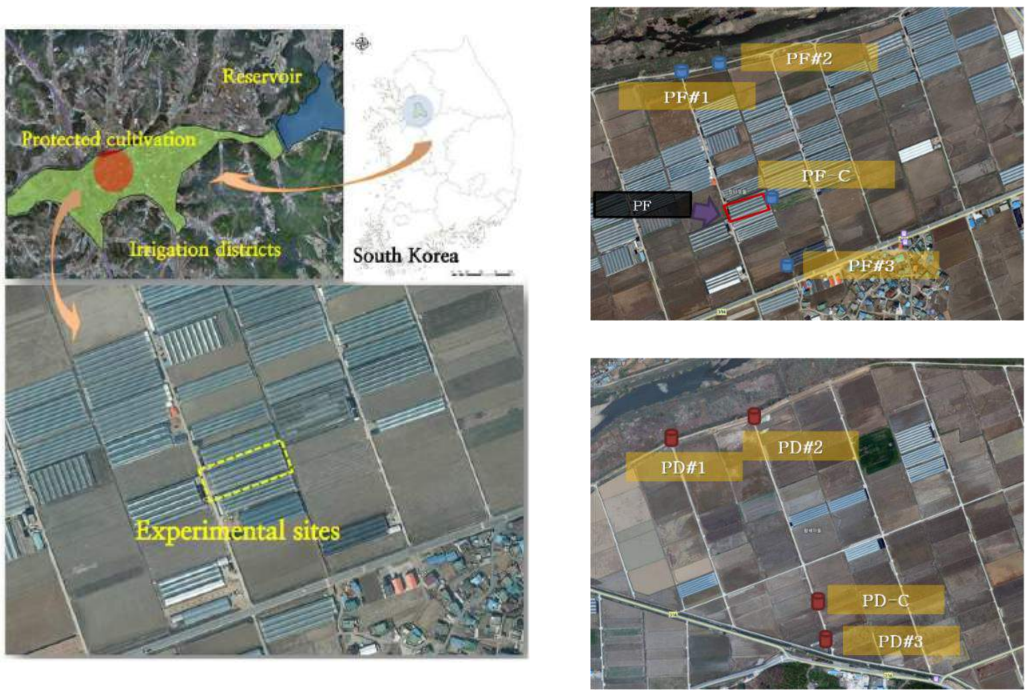


Figure1. Location map of the experimental sites: protected farming and paddy fields

This study was conducted in protected farming cultivated area located in Namsa-Myeon, Cheoin-Gu, Yongin-Si, and Gyeonggi-Do, South Korea (E 37°06′04″, N 127°08′08″) as shown in Fig. 1. This area was a traditionally rural area mainly cultivated rice paddies, but recently the land use has changed to protected farming cultivation for vegetables and flowers. The 30-year average annual temperature in the study area is 11.4˚C and annual precipitation is approximately 1312.2 mm and rainfall is mainly concentrated in the summer season from June to September. The soil type in the study area (RDA SIS, http://soil.rda.go.kr) is classified as the Seogcheon (SE) series (*coarse loamy, mixed, nonacid, mesic Fluvaquentic Endoaquept*). According to the farmer's interview, irrigation/fertigation in protected farming fields occurred every 2 or 3 days for 2 or 3 hours and crops are cultivated two rotations a year

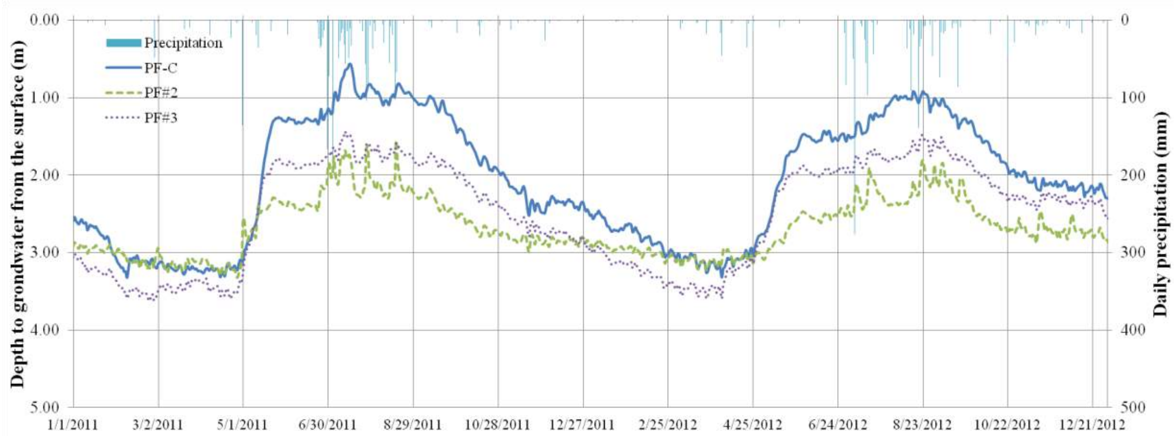
Monitoring system layout

To monitor shallow groundwater drainage and its water quality, soil moisture content on protected farming experimental site, and shallow groundwater level and quality were monitored and analyzed as shown in figure 1. Volumetric soil moisture content (%) was measured using a Frequency Domain Reflection (FDR) probe (EnviroSMART soil moisture probe, Sentek Pty. Ltd., Adelaide, Australia) at 60 and 90 cm soil depth in every 15 minutes. Shallow groundwater level at 8 different sites (4 points near protected farming area and 4 points on paddy fields) were monitored every 1 hour and water samples were collected biweekly. The samples were analyzed at the Seoul National University National Instrumentation Center for Environmental Management (NICEM). The EC (ECw, electrical conductivity of the soil solution) and the concentrations of NO_3-N, T-N, and T-P were determined for the shallow groundwater samples.

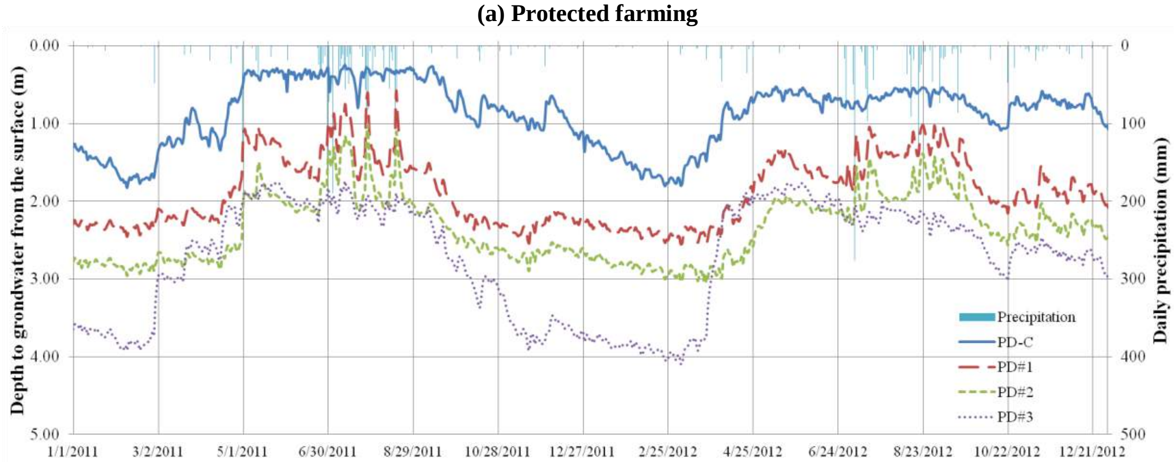
Results and discussion

Shallow groundwater drainage

The elevation of shallow groundwater in protected farming fields were 14.9 m in PF-C, 14.2 m in PF#1 and PF#2 and 15.5 m in PF#3. The elevation of shallow groundwater in paddy field area were 16.7 m in PD-C, 14.1 m in PF#1, 14.9 m in PF#3 and 17.7 m in PF#3. Figure 2 is the temporal variation of depth from surface to shallow groundwater in protected farming and paddy field area. The depth and pattern of fluctuation of shallow groundwater are similar between protected farming and paddy field area. It has increased during the wet season accordance with precipitation event and decreased on the dry season. In particular, on the monitoring points of PF-C located behind of site, shallow groundwater has increased and the depth was less than 1.0 m during the wet season. As shown in figure 3, when the depth to shallow groundwater was less than or near 1.0 m (on June-August), the soil moisture content tends to be almost saturated even rainfall is intercepted due to frequent irrigation/fertigation and high groundwater level. There is the possibility of nutrient accumulation and subsequent leaching into the shallow groundwater.



(a) Protected farming



(b) Paddy field

Figure2. Temporal variation of depth to shallow groundwater table from surface in protected cultivation and paddy field area

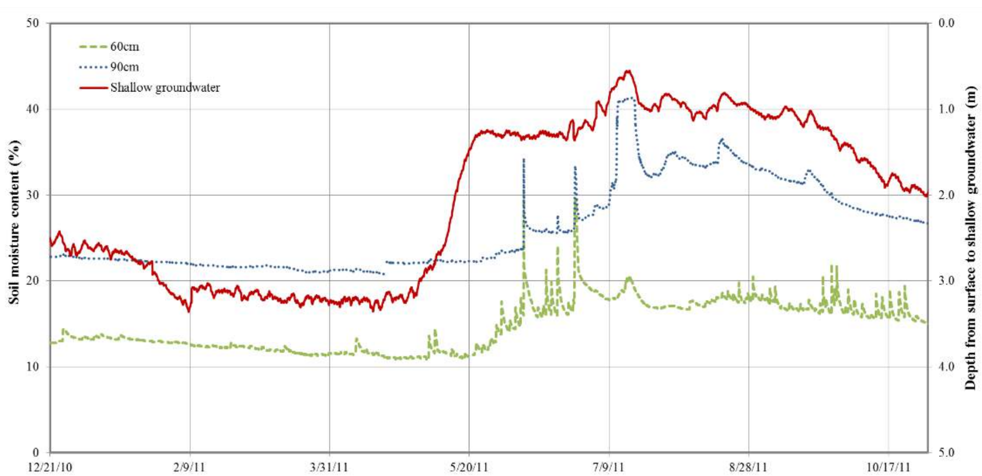


Figure3. The comparison between soil moisture content at 60 and 90 cm soil layer and depth from surface to shallow groundwater at PF-C

Shallow groundwater quality

Table 1 shows the average and standard deviation nutrient concentrations of shallow groundwater at 8 different sites. TP concentration on paddy field was higher than on protected farming sites. However, EC and other nutrients (NO_3-N, TN, etc.) on protected farming were higher than on paddy field, even though the depth and level of shallow groundwater were similar between two sites. The EC and NO_3-N levels are the main factors that influence shallow groundwater contamination through leaching in protected cultivation (Kim et al., 2008; Hong et al., 2014). In particular, excess NO_3-N leaching into groundwater can cause many problems including cyanosis (Kurunc et al., 2011).

EC is correlated with salinity. Excessive salinity can cause nutrient absorption and inhibiting plant growth when utilized as irrigation water. According to the USDA, irrigation water with an EC greater than 2.25 dS m^{-1} is difficult to use for agricultural purposes (US Salinity Laboratory Staff, 1954). According to the FAO, an EC greater than 3.0 dS m^{-1}has adverse effects on crop growth (Ayers and Wescot, 1995). The EC in protected farming fields has similar pattern and no fluctuations or trends and the average EC was less than 1.0 dS m^{-1} and regulation for irrigation from USDA and FAO.

Protected farming cultivation tends to apply high volume of irrigation and high frequency and nutrient levels in fertigation (Hong et al., 2014). As a result, nitrate leaching and nutrient concentrations are much greater in protected farming cultivation than in paddy fields (Sun et al., 2012). The average NO_3-N concentration of shallow groundwater in protected farming fields are 0.24-3.39 mg l^{-1}which are higher than in paddy fields (0.05-0.67 mg l^{-1}). As shown in figure 4 and 5, the NO_3-N concentration at PF-C behind the protected farming cultivation site has been increased during the summer season with high precipitation and groundwater level. According to Hong et al., (2014), excess nutrients with excess fertigation have accumulated in the root zone and the NO_3-N concentration below 90 cm soil layer has increased during the summer season. The NO_3-N concentration in these season was also increased with the increasing of shallow groundwater level. It may have been affected by the nutrients accumulation and drainage from the soil water to shallow groundwater as the elevation of the shallow groundwater level is increased.

Table 1. Average and standard deviation EC and nutrient concentrations (TN, NO_3-N, and TP) in the shallow groundwater

Location	EC (dS m^{-1})		TN (mg L^{-1})		NO3-N (mg L^{-1})		TP (mg L^{-1})	
	avg	std	avg	std	avg	std	avg	std
PF-C	0.37	0.12	3.01	2.23	2.82	2.12	0.02	0.03
PF#1	0.55	0.07	0.32	1.18	0.24	1.09	0.02	0.01
PF#2	0.35	0.10	1.01	3.16	0.94	3.14	0.02	0.03
PF#3	0.51	0.10	3.80	1.81	3.39	1.62	0.03	0.02
PD-C	0.16	0.04	0.28	0.39	0.17	0.36	0.22	0.31
PD#1	0.33	0.08	0.28	0.58	0.13	0.29	0.04	0.03
PD#2	0.47	0.08	0.25	0.90	0.05	0.13	0.08	0.09
PD#3	0.22	0.09	0.82	1.02	0.67	0.97	0.04	0.05

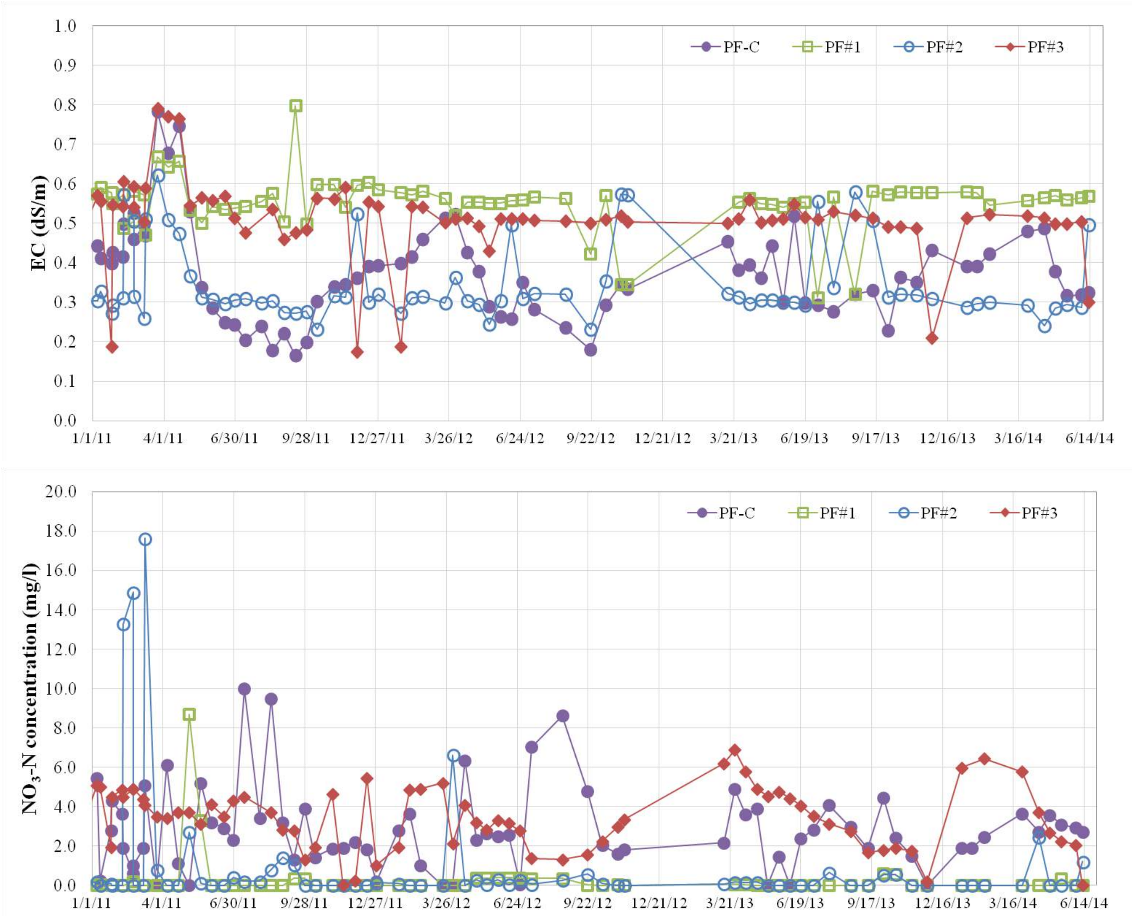
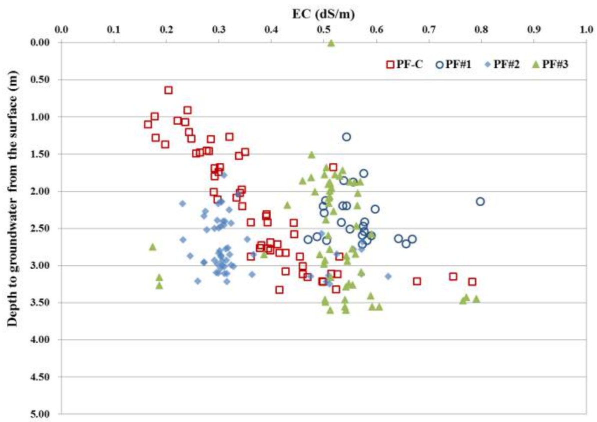
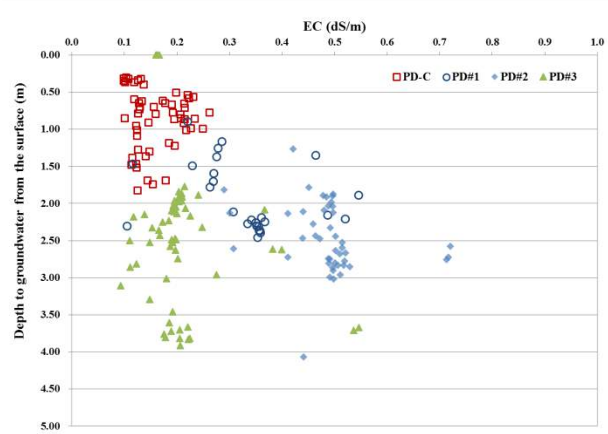


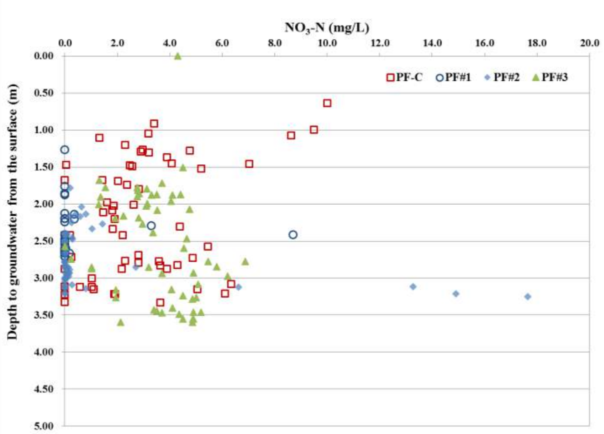
Figure 4. EC and NO_3-N temporal changes of shallow groundwater



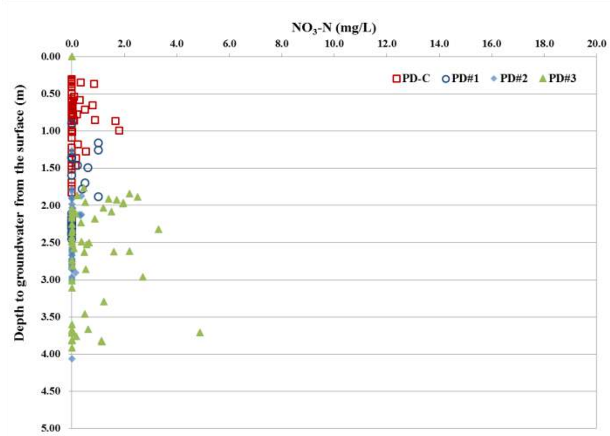
(a) EC (PF)



(b) EC (PD)



(c) NO_3-N (PF)



(d) NO_3-N (PD)

Figure 5. Comparison between EC and NO_3-N and depth to groundwater from the surface

Most environmental factors, weather conditions, irrigation, and fertilization, can be controlled in protected cultivation. However, NO_3-N, which is one of the most important factors controlling crop growth, is difficult to retain in a soil layer because its movement depends on the mobility of soil water (Hong et al., 2014). Therefore nutrients such as NO_3-N can leach into the lower soil layers and enter shallow groundwater, which has a higher elevation than confined groundwater (Tan et al., 2012).

Conclusion

In protected farming cultivation in Korea, the excess of nutrients is becoming increasingly serious. The purpose of this study was to monitor and analyze shallow groundwater drainage and water quality at protected cultivation fields. This study found that even NO_3-N and other nutrient concentration in protected farming fields were less than the groundwater regulation for irrigation, however, it and its standard deviation and variations were higher than in paddy fields.

In particular, the NO_3-N concentration on PF-C behind the protected cultivation site during the summer wet season has been increased with increasing of groundwater lever. It is considered that the nutrient concentration on shallow groundwater may be influenced by nutrient accumulation by over fertilization or drainage according to the irrigation or fertigation.

There is a possibility of shallow groundwater pollution if conventional management of protected farming practices continued. This study can inform guidelines to reduce the agricultural non-point pollution load, manage shallow groundwater and aid in the development of a model for analyzing agricultural non-point pollution from protected farming cultivation.

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THE STUDY OF WATERMELON CROP RESPONSE UNDER SHALLOW WATER TABLE AT INITIAL GROWTH FOR DEVELOPING DRAINAGE PLANING AT TIDAL LOWLAND AGRICULTURE

Momon Sodik Imanudin[1,*], M. E Armanto[2], R. H Susanto[3]

Abstract

Water melon cultivation is one of the suitable alternatives applied in order to increase farmers income in tidal lowland agriculture zones. The research of crop adaptation to wet soil conditions is required so that farmers will be able to decide the best planting time based on the existing land typology conditions .. The research focuses on the determining of crop physiology response during its initial growth period within a greenhouse. The treatments consisted of water table depths at 15, 10 and 5 cm below soil surface, respectively. The observation of water table surface was carried out in the field. Analysis of crop potential based on water status condition in the root zones was conducted using secondary and primary data. The results of crop adaptation at a shallow water table depth showed that treatments of water table at depths of 10 cm and 5 cm were not signficantly different in terms of crop height with a magnitude of 12.6 cm and 12.3 cm having respectively 3 leaves. However, it had a significant effect on root length with a magnitude of 11.9 cm and 3.1 cm, respectively. The Maximum crop height of 15.2 cm and 4 leaves was found upon the treatment at 15 cm water table depth. It can be concluded that farmers are advised to plant on the basis of the water table conditions of 10 cm below the soil surface. The objective of accelerated planting is that crops do not need irrigation water at a generative phase. This condition is especially recommended for C land typology which had a high porosity and low capillary flow.

KEY WORDS: Tidal lowland, Watermelon, Water table, Drainage.

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Introduction

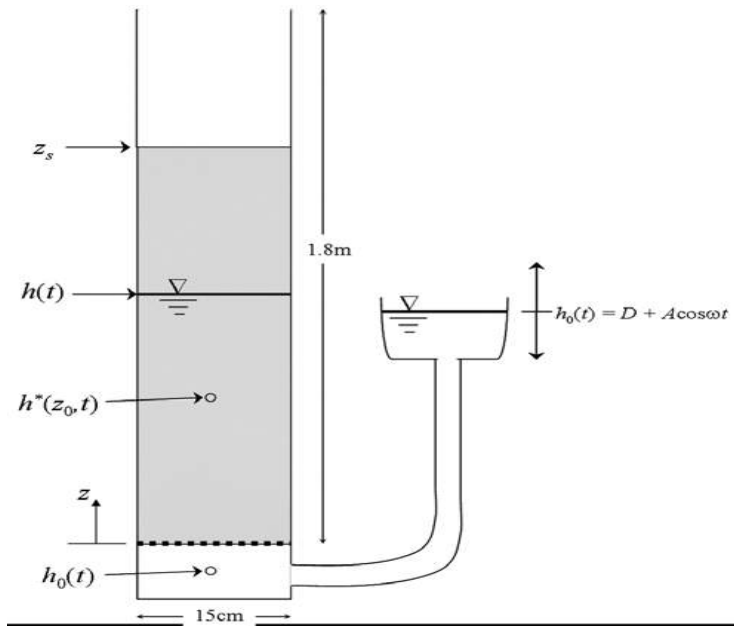
Agriculture enterprise in tidal lowland area had faced the main constraint in form of land use conversion from food crops to plantation crops. One effort of controlling land use conversion in tidal lowland agriculture is to increase the planting intensity. The study by Imanudin *et al.* (2010; 2011) at tidal lowland of Delta Telang II showed that land had high potential for two or even three times planting. The change of planting pattern into two times planting could produced equal income compared to income from oil palm crop. The change of planting pattern from *rice-fallow* into *rice-corn* and *rice-corn-corn* was more profitable (Imanudin and Bakri, 2014). Crop diversification with watermelon provided new prospect for farmers because it could produced higher income than that of oil palm plantation. The profit gained from watermelon cultivation can be as high as 30 million rupiahs/ha with duration of 70 to 90 days. According to Gunawan (2014), if watermelon production is 11 tons and its price is 3000 rupiahs/kg, then the net profit received by farmers was about 18.5 million rupiahs. Therefore, watermelon cultivation effort at wet land is necessary as an alternative of farm enterprise diversification.

Tidal lowland area with shalow water table has high potential for watermelon cultivation. Soil water contribution through capilary flow is sufficient to provide crop water requirement (Imanudin and Bakri, 2014). This condition has advantage because irrigation for land is not needed resulting in cost saving. However, if delay planting is occurred during flowering phase at dry season in which water table has exceed the critical level (150 cm), then irrigation pump should be provided (Singh *et al.*, 2006). However, long period of flooded condition results in abiotic stress for crop, affects sprout growth rate, seed development and subsequently affect crop growth and development, especially at initial growth period (Dat *el al.* 2006). Crop is capable to tolerate water content level which exceed 25% higher than field capacity (Prawoto *et al.*, 2005). Information related to water melon tolerance level to water content condition higher than that of field capacity is not yet available up to nowadays.

Based on the above discussion, basic research is required to determine watermelon crop response at initial phase to shallow water table condition. Information related to minimum depth of water table for crop planting is very important for farmers to determine the planting date.

Materials and methods

Materials and equipments used in this study were soil media having sandy loam texture, water melon seeds, water and aqua bottles. Equipment design for water table level control was produced by using continous flow system (Figure 1) in which soil water level within soil media is made in equilibrium with soil water level in reservoir using the principle of connected vessel. Analysis of soil water contribution through capillary movement (Figure 2).



Source: Udom *et al*. (2013)

Figure 1. Exprimental set up of soil water contribution to supply crop water requirement.

Figure 2. Exprimental application of soil water depth to supply irrigation for crop

Treatments of soil water depth were consisted of 5, 10 and 15 cm below soil surface. Soil water depth in the range of 5 to10 cm is frequently found in the field at land condition after rice harvesting which is usually occurred in March-April.
In order to maintain constant value of soil water treatments, then water height in column should be kept constant which require daily observation. Crop growth is observed and height as well as leave numbers will be measured at two weeks after planting. Root length and leave numbers of crop for each treatment will be observed at the end of expriment. Data analysis of daily water table level was done to determine planting potential in the field. Data of daily water table level was obtained from secondary data (Imanudin, 2010) and direct observation of daily water table level at Telang II area in 2015. Data of daily water table level would also be compared with rainfall data in 2015. Rainfall data was obtained from Kenten Climatology Station of Palembang.

Experimental site

Research was conducted in the greenhouse at Agroecotechnology Department, Faculty of Agriculture, Sriwijaya University from March to April 2016. Data of daily water level from secondary data and direct observation was used to analyze planting time. Direct observation was done at tertiary plot of Delta Telang II, Mulya Sari Village, Banyuasin District.

Results and discussion

Study of Planting Potential in Tidal Lowland Area

Water melon cultivation in tidal lowland area so far is highly depend on season. Planting in wet season can not be implemented due to very high soil water level as a results of rainfall effect although high tidal water was blocked to prevent water from entering the land. High rainfall intensity couple with insufficient duration of low tidal water for water discharging results in full water within channel and difficulty of water table drawdown. Figure 3 showed data of water table fluctuation in February to March at B land typology in 2015 which was highly affected by rainfall. Observation area was at Delta Telang II. The drastic upward flow of water table was due to rainfall. Water table would continously drop in case of no rainfall. This condition showed that micro water management system was relatively effective in lowering of water table level. Micro water management system was developed by constructing small channel (called *micro channel*) for every 8 m distance having depth of 20 cm. Tertiary channel has function to collect rainfall water and water gate in tertiary channel has function to discharge water. However, farmers could not capable to do planting in early March because average depth of water table was less than 10 cm below soil surface. Figure 3 also showed that water was flooded for 10 to 12 days. Direct planting of water melon seeds could not be done in this condition. Planting can be done at 14th day or in middle of March.

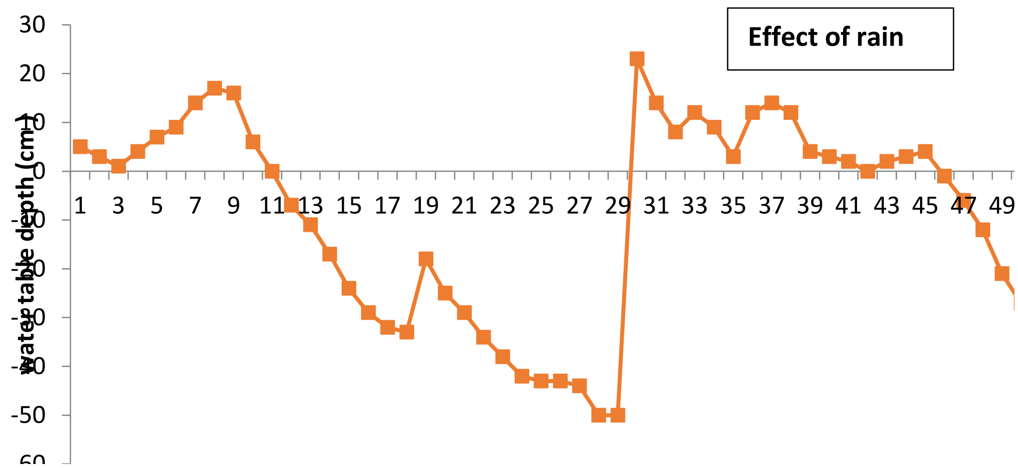


Figure 3. Water table condition in March 2015 at dry climate condition.

Figure 4 showed water table level observation at Telang I area in 2009 which indicate that water table was extremely saturate up to May for crops cultivation, except for rice cultivation. Planting can be done in last of May or early of June so that crop frequently experienced dryness during generative phase in August. According to Bakri *et al.*(2015), water management objective was as water retention within tertiary channel for crop cultivation at tidal lowland area in period of June-September. If high tidal water still capable to enter tertiary channel, then proper water gate is stoplog system with retention level of 50 cm depth. Stoplog height is regulated so that high tidal water can enter the channel and water was held at minimum of 50 cm depth during low tidal water period. If automatic fibre flap gate is available, then gate position is located in rear side facing the land at dry season so that high tidal water can enter the channel and gate will automatically closed during low tidal water. However, this gate is easily damage and it can not be repaired by farmers (Imanudin *et al.*, 2015b).

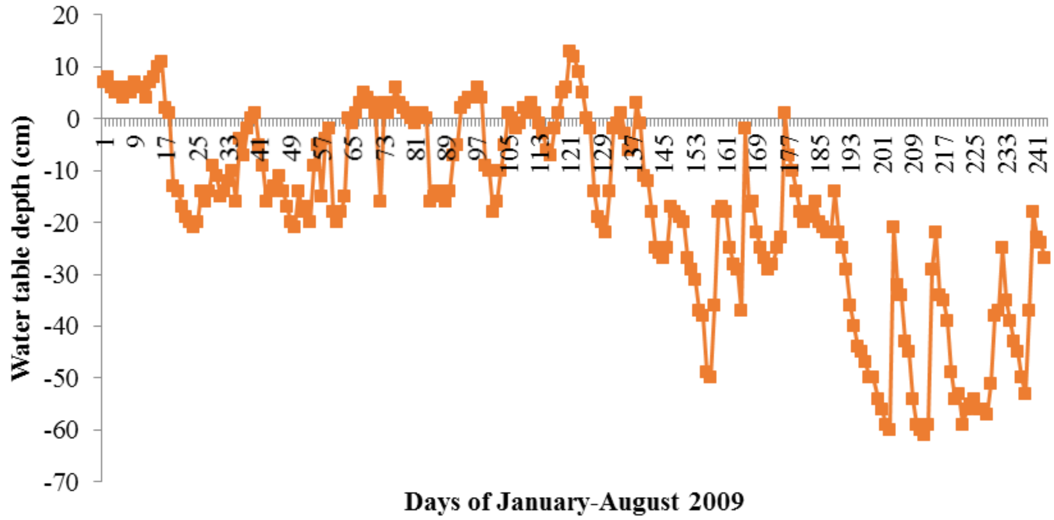


Figure 4. Water table condition during January-August period at normal climate condition (Imanudin et al, 2010).

Planting should be done at the end of wet season in April or even in March due to dry season as a results of El Nino effect in 2015. Crop adaptation in early growth period to wet condition should be conducted. The effort to move foward this planting time is done to prevent water deficiency at generative growth phase. Dry climate condition in August-September cause soil water content in root zone was close to permanent wilting point condition due to the decrease of capillary potential because water table position was dropped to more than 150 cm (Figure 5). Rainfall was start decreasing entering July and the maximum decrease was occurred in August-September-Okrtober (Figure 6). Wang *et al.* (2004) reported that irrigation effort is needed for crop cultivation if rainfall is less than 120 mm. Irrigation water with magnitude of 68 mm will capable to increase production by 46%. Irrigation water couple with mulch can increase production with magnitude of 11.4 ton/ha than that of without mulch addition.

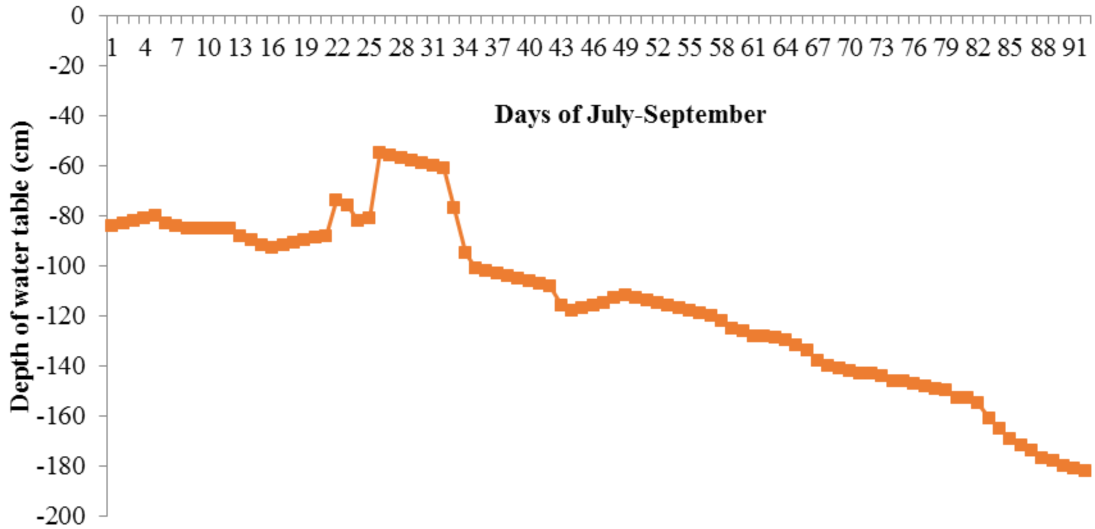


Figure 5. Water table condition at dry season in 2015 in land typology B

Relationship between soil water existence and evapotranspiration rate showed that the closer soil water to soil surface, the higher was the crop evapotranspiration rate. Karimova *at al*. (2014) had reported for the case of loamy clay soil that soil water position at 1.5 m below soil surface had evapotranspiration value of 47% and at position 3 m below soil surface had evapotranspiration value of only 23%. This finding showed that crop requires addition of irrigation for maximum evapotranspiration at those positions.

Results of study by Singh *et al*. (2006) on Typic Haplustalf soil with clay content of 45% showed capillary water movement with magnitude of 18.7 mm/day at soil water depth of 90 cm below soil surface and soil water contribution was decreased to 10.7 mm/day at soil water depth of 120 cm below soil surface. Soil water contribution on sandy clay soil at soil water depth of 0.74 m below soil surface was 4.76 mm/day and its contribution was 2.45 mm/day at soil water depth of 1 m below soil surface (Udom *et al.*, 2013). These data showed that soil water movement at condition of 100-120 cm below soil surface is sufficient to fulfill crop evapotranspiration requirement. However, crop will require addition of irrigation water if soil water condition was located more than 200 cm below soil surface. Therefore, water retention function to keep soil water located at 100-130 cm below soil surface is very important if farmers conduct crop cultivation during dry season. Planting intensity can be done two or even three times as an impact of this land and water management. Intensive farm enterprise can decrease forest and land fire indirectly if land is properly managed and utilized (Imanudin and Susanto, 2015).

Experimental Study of Water melon planting test at shallow water table condition

The basic consideration for the test is earlier planting of water melon during wet season period in March or early April (see the Figure 6). It is hoped that acceleration of this planting time can prevent dryness during the plant flowering and harvesting phases. The third planting times for watermelon or corn can be done in case of normal climate condition. Testing of crop response was conducted within greenhouse. Two treatments of soil water depth were implemented consisting of 5 cm and 10 cm below soil surface.

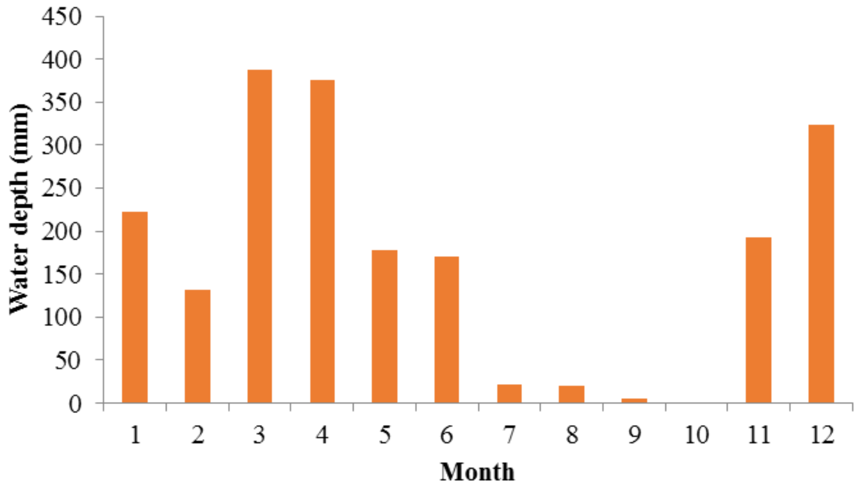


Figure 6. Rainfall condition at the study area (source: Kenten Climatology Station, 2016)

Crop testing results for two soil water status mentioned above showed that crop can still grow at soil water depth of 5 cm below soil surface with under optimum growth level. Watermelon crop had already growth at the 4th day for soil water depth of 10 cm below soil surface, but it did not grow for soil water depth of 5 cm below soil surface. Crop height was 5.6 cm and its leave was still cringe (closed) with uplifted seed skin at the 6th day for soil water depth of 10 cm below soil surface, but stem prospective was just emerging for soil water depth of 10 cm below soil surface. Crop height was 12.1 cm with 3 leaves at the 17th day for soil water depth of 10 cm below soil surface, whereas crop height was 8.2 cm with 3 leaves addition at the 17th day for soil water depth of 5 cm below soil surface. Average growth rate of crop until the 17th day for soil water depth of 10 cm below soil surface was 0.71 cm/day and its value was 0.48 cm/day for soil water depth of 5 cm below soil surface. Crop growth description can be seen in Figure 7.

-5 cm -10 cm -15 cm

Figure 7. Visualization of watermelon respond to shallow water table condition (15th day)

Laboratory expriment was stopped after 20 days of planting time because it is estimated that water table drawdown was dropped more than 20 cm below soil surface at field condition. This period was entered the end of wet season (April) if farmers did planting at the end of March. Plant can be more adaptive to environment condition at this period. Observation at 20th day was conducted on watermelon crop treated with water table depth of 15 cm below soil surface. Crop height was 15.2 cm and had 4 leaves at 20th day observation. The crop had more leave numbers at this treatment than that of 10 cm and 5 cm below soil surface treatments. Humphries *et al.,* in Gardner *et al.,* (1991) had stated that leave numbers and size were affected by genotype and environment. The leave position on crop which is primarily controlled by genotype also has effect on leave growth rate, final size of leave and better response capacity to environment such as water availability. Crop which capable to produce higher photosynthates will produce more leave numbers because photosynthates will be used to develop crop organs such as leave and trunk in accordance to the increase of crop dry matter weight (Hasanuddin *et al. in* Firda, 2009).
Average growth rate of crop height was 0.76 cm/day for 15 cm below soil surface treatment. This value was relatively similar to the result obtained from 10 cm below soil surface. Therefore, watermelon cultivation can be started if field condition showed water table depth of 10 cm below soil surface. The contrast condition was found on 5 cm below soil surface treatment which showed the stopping growth of root elongation. The root crop length was only 3.1 cm at 20 days after planting which indicated that root growth avoids water table level.

The ideal condition for crop growth is at available water condition which located between field capacity and permanent wilting point. Crop growth at initial phase will be disturbed if soil humidity status is at 75% level of exhausted available water condition, whereas optimun crop growth is at 50% level of exhausted available water condition (Modi and Zulu, 2012). It was reported that soil with continous high water content had potential to experience deficiency in macro nutrients such as N, P, K, Ca and Mg as well as toxicities of Fe and Al (Hairunsyah, 1987). Some of these macro nutrients had structural role, for instance Mg as porfirin core composer within chlorophyl, N as the main element of amino acid, protein and enzyme composers, whereas Ca as the main composer of crop cell wall. The subsequent effect of this soil condition will characterized by decrease of chlorophyl content, yellowing, drying and falling leaves as well stopping of plant's prospective growth.

Crop which flooded within short time will experience hypoxia condition (lack of O_2). Hypoxia is usually occurred if part of crop roots is flooded (crown part is not flooded) or crop is flloded for long time but crop roots are located near soil surface. If all part of crop is flooded, then crop roots is located further deep in soil and experience flooded for longer time so that crop was at anoxia condition (without O_2 environment). Anoxia condition is occurred 6 to 8 hours after flooded because O_2 is suppressed by water and the rest of O_2 is utilized by microorganisms. The left over O_2 content within soil at flooded condition with availability of crop is used up faster because O_2 diffusion rate within wet soil is 10,000 times slower than O_2 diffusion rate in air (Amstrong 1979 *in* Dennis et al., 2000). Condition of hypoxia or anoxia not only prevent N fixation, but also distribution of N and other minerals which in turn impede root growth and nodulation. Leave will experience yellowing followed by leave falling due to insufficient transportation of N and minerals into crown part. Scott *et al*. (1989) had reported that flooded effects were indicated by leave yellowing, leave falling at the lowest joint, dwarf and decrease of dry matter weight and crop yield. According to Hapsari and Adie (2010), results study for soybean crop showed that yield losses in general at vegetative phase was lower than that of reproductive phase having respective values of 17 to 43% and 50 to 56%. The magnitude of yield losses was depended on crop variety, crop growth phase, flooded period, soil texture and the existence of crop weeds and diseases.

Potential time planting at land thypology C

Results from greenhose experiment showed that watermelon can be planted at condition of shallow water table within 10 to 15 cm below soil surface. If watermelon cultivation will be conducted at C land typology in tidal lowland area, then planting time can be accelerated in the end of February or planting was directly conducted after rice harvesting at first planting period. Planting can be done by using hole system in which rice straw was cleared and micro channel was developed for every 6 to 8 m using single plow equipment. Planting time should be quick in order to prevent dryness. Harvesting is estimated in the end of May if planting is done in the end of February or early of March. Generative phase would be in May. Observation results of water table level fluctuation (LWMTL, 2006) showed that planting time could be done in early of March in which water table level was located 20 to 30 cm below soil surface. Planting actually can be done in February based on water table data, but it is better to be done in early of March because farmers were busy in activity of first season rice harvesting in February. Land area with C land typology is highly depend on rainfall. Water supply from high tidal water could not be provided because average height of high tidal water could not flooded into the land. Water retention in channel should be provided in order to maintain water table position close to roots zone.

Flowering phase in May had pose high risk because water table is frequently dropped into 90 to 100 cm below soil surface (Figure 8). Therefore, irrigation was needed in this phase for at least two times application. Irrigation by using pump (or pump irrigation) would be very helpful in this condition in which water was pumped from tertiary channel using furrow irrigation system application. High soil porosity in this C land typology at tidal lowland caused capillary water was not sufficiently available to fulfill crop evapotranspiration requirement if the depth of water table was 100 cm below soil surface.

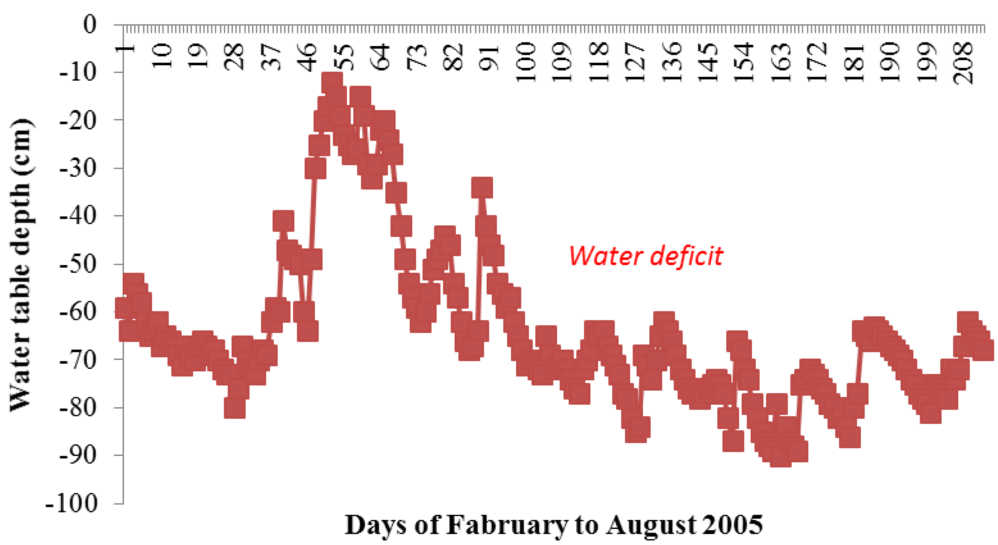


Figure 8. Water table fluctuation at C typology of tidal lowland area (LWMTL, 2006).

According to Pasribu *et al.* (2013), crop water requirement (Etc) for watermelon is 2.80 mm/day for initial growth phase, 6.23 mm/day for middle growth phase and 4.36 mm/day for final growth phase, respectively. Results of study by Singh *et al*. (2006) showed that soil water contribution was 10.7 mm/day if water table depth was 120 cm below soil surface for dominated clay textural soil. On the other hand, capillary water contribution was 4.76 mm/day if water table depth was 74 cm below soil surface and 2.45 mm/day if water table depth was 100 cm below soil surface for sandy loam soil (Udom et al., 2013). This condition showed that critical level of water table depth for crop was 100 cm below soil surface for C land typology, whereas critical level of water table depth for crop was 150 cm below soil surface for B land typology which was dominated by clay soil. Analysisi results of water table fluctuation showed that crop (watermelon) cultivation can be done without irrigation water addition at B land typology (Figure 9).

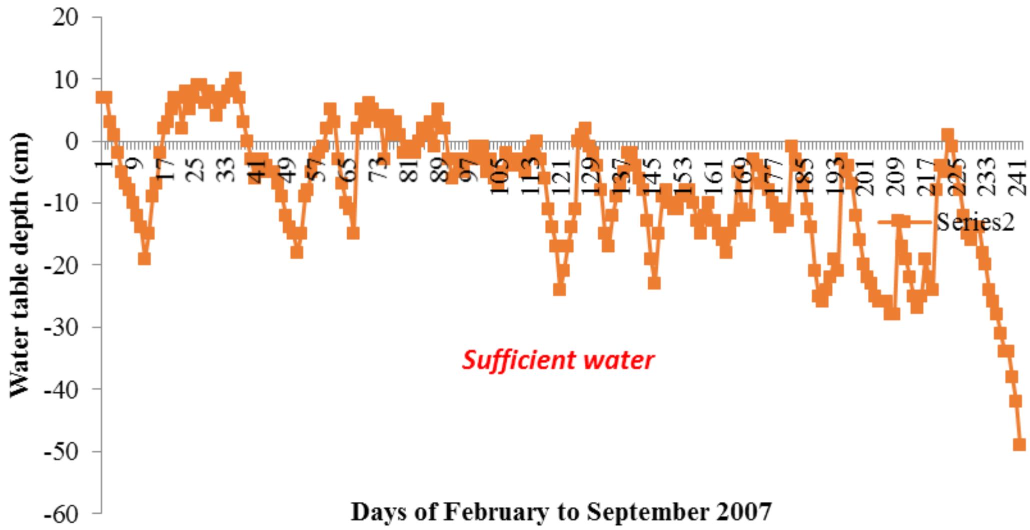


Figure 9. Water table fluctuation at B land typology (Imanudin *et al,* 2010)

Conclusion

- Watermelon crop had potential to be developed in tidal lowland area because it was relatively tolerant to shallow water table depth at initial growth phase. This crop was capable to grow at water table depth of 5 cm below soil surface. The optimum growth was achieved at water table depth of 15 cm below soil surface. However, field application showed that watermelon could be planted at water table depth of 10 cm below soil surface. Results of field study showed that water table depth for B-C land typlogies had achieved 15 cm below soil surface in March-April. Accelerated planting in the end of March was very important in order to prevent dryness occurrence for crop at generative phase because gravitational irrigation system could not be applied to most of tidal lowland areas.
- Crop adaptation to water table is vary depending on planting time and land typology. Crop could be planted in June and was harvested in September without irrigation water provision for A and B land typologies. Capillary water at these land typologies was sufficient to fulfill evapotranspiration requirement. However, earlier planting time in March and harvesting in May-June should be conducted at C land typology because this land had high soil prosity. Capillary water during dry season in this soil could not fulfill evapotranspiration requirement. Water table level in June-September could achieved more than 120 cm below soil surface.

- The tertiary channel should be equipped with water gate to control the proposed water table depth. The main option for A and B land typologies was drainage, whereas for C land typology was water retention.

Acknowledgement

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IMPORTANT ROLE OF THERMAL REMOTE SENSING (TRS) IN IRRIGATION AND DRAINAGE PROJECTS (CASE STUDY: MINOO ISLAND)

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Abstract

Temperature as one of the most important thermodynamic factors effect on some environmental parameters like rate of physical and chemical reactions, dissolution of minerals and evapotranspiration by soils and vegetation strongly. In design of irrigation and drainage systems, estimation of water requirement for cultivation of crops based on cultivation pattern, in order to avoid of water logging, water shortage and excessive consumption of water and produce run-off more than capacity of drainage system is essential, therefore accurate estimation of evapotranspiration is necessary, especially in arid and semiarid climate like Khuzestan province to manage water resources intelligently. As usual in irrigation and drainage projects, temperature data recorded by meteorological stations is used to estimate evapotranspiration by Penman-Monteith equation, these stations recorded temperature as spot in a small spatial scale and land cover variety does not consider in large spatial scale. Exactly because that, engineers and designers should be careful in using of data obtained by meteorological stations in big scale especially when distance between meteorological stations is away. One of the most effective and newest tools to investigation about land surface temperature (LST) is thermal remote sensing, this technology is related to remote sensing science that process and interpret data obtained in the thermal infrared region of the electromagnetic spectrum is used and can be applied as an alternative or at least complementary selection. This study is done aimed to mapping and classification of land surface temperature pattern in lands scope of Minoo Island. In order to evaluation of land surface

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temperature in Minoo Island, Landsat satellite images (OLI sensor) was used. We compared two recent thermal images acquired in 07/11/2015 and 07/13/2016 before and after logging operation respectively to show dynamic of temperature pattern in spatial and temporal scales. Results of this research demonstrated there was an important different between these two patterns before and after logging operation, as different period of time, pattern of LST changed with regards to land use too, in other words we observed for same places before and after logging operation (variability of time) and according to land use (variability of location) a difference between 8 to 10 C^{o}. These results show importance of spatial and temporal changes of temperature and its role to effect on water requirement, especially in Iran plateau. Finally, authors recommend strongly application of TRS technology as an alternative for or at least a complementary method beside of traditional methods to estimation evapotranspiration by databases like NETWAT that is based on meteorological stations data provided as spot small scale.

KEY WORDS: TRS, Irrigation, Drainage, Water Management, Temperature.

Introduction

Temperature as one of the most important thermodynamic factors effect on some environmental parameters like rate of physical and chemical reactions, dissolution of minerals and evapotranspiration by soils and vegetation strongly. In recent decease application of thermal remote sensing (TRS) has been developed to study and research about environmental changes. Land surface temperature (LST) mapping by remote sensing technology have been used frequently to determine spatial pattern of temperature, developing models of LST exchange, and analyzing the relationships between temperature, land use and land cover in agricultural areas. Recent researches have demonstrated relationships between spatial pattern of temperature and surface features such as vegetation indices and moisture content of soils. Recent researches inquired the effect of biophysical parameters on spatial pattern of temperature by application of essential surface factors such as vegetation index instead of postural land use classes (Amiri et al, 2009). The vegetation index–LST relationship has been used by some scientists (by Carlson et al. (1994) to recover and regain surface biophysical factors, by Kustas et al. (2003) to adapt sub-pixel thermal variations, and by Lambin and Ehrlich (1996) to survey land cover dynamics). Many researchers have reported a reverse relationship between vegetation and LST, this results motivated other researches into two major fields: statistical analysis of the relationship and the temperature/vegetation index (TVX) approach. TVX by definition is a multi-spectral method of combining LST and a vegetation index (VI) in a scatterplot to observe their associations (Quattrochi and Luvall, 2004).

According to World Bank report (World Bank, 2014), global temperatures are 0.8 °C above pre-industrial temperatures. Based on past greenhouse gas emissions and current trends, a further atmospheric warming to 1.5 °C above pre-industrial levels is expected in the short term. In absence of concerted action to reduce emissions, global warming is expected to be around 2 °C by 2050 and 4 °C by 2100. No region will be spared from this change and the adverse effects of this phenomenon will be felt on agriculture, water resources, ecosystems, and human health, especially in regions that are already the most vulnerable, such as semi-arid areas. Proper water resources management is important in reducing vulnerability to drought and other extreme events that may occur with increasing frequency as a consequence of climate change. Arid and semi-arid regions of the Middle East area are already significantly affected by climate change according to the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2014). It is expected that these regions will become drier and warmer, thus putting even more pressure on already vulnerable water resources (Dong *et al.,* 2013; IPCC, 2014; Ludwig *et al.,* 2011; Olsen *et al.,* 2011; World Bank, 2014). Changes in the hydrological cycle will lead to an increasing risk of tension and conflict in social, ecological, political, and economic spheres (Dong *et al*., 2011; Ludwig *et al*., 2011).

In design of irrigation and drainage systems, estimation of water requirement for cultivation of crops based on cultivation pattern, in order to avoid of water logging, water shortage and excessive consumption of water and produce run-off more than capacity of drainage system is essential, therefore accurate estimation of evapotranspiration is necessary, especially in arid and semiarid climate like Khuzestan province to manage water resources intelligently. Development and implementation of effective adaptation and preventive policies requires interdisciplinary collaboration and exploitation of advanced technologies for environmental monitoring, modeling, and analysis. This study is done aimed to mapping and classification of land surface temperature pattern in lands scope of Minoo Island. In order to evaluation of land surface temperature in Minoo Island.

Material and Methods

Minoo is an Island in the Khuzestan province, in southwestern Iran and is close to the city of Abadan. Minooshahr is on the island, in recent months, project of irrigation and drainage of Minoo lands started, this location is a strategic location (Fig 1).

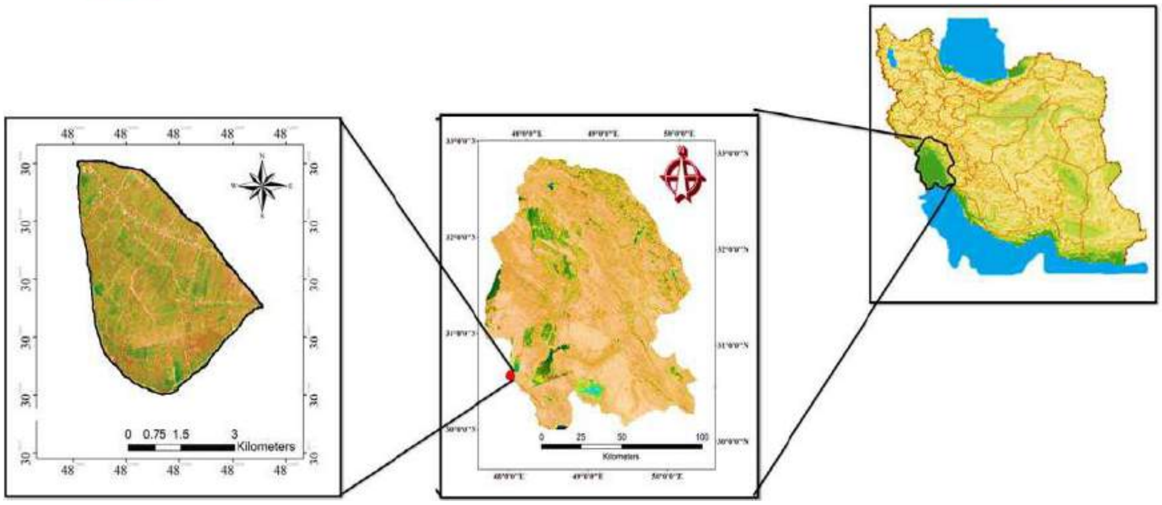

Fig1: schematic location of Minoo Island

There are not enough information about Minoo environment and ecosystem and because of this project there are a few valuable data now. As usual in irrigation and drainage projects, temperature data recorded by meteorological stations is used to estimate evapotranspiration by Penman-Monteith equation, these stations recorded temperature as spot in a small spatial scale and land cover variety does not consider in large spatial scale. Exactly because that, engineers and designers should be careful in using of data obtained by meteorological stations in big scale especially when distance between meteorological stations is away. One of the most effective and newest tools to investigation about land surface temperature (LST) is thermal remote sensing, this technology is related to remote sensing science that process and interpret data obtained in the thermal infrared region of the electromagnetic spectrum is used and can be applied as an alternative or at least complementary selection. In order to evaluation of land surface temperature in Minoo Island, Landsat satellite images (OLI sensor) was used. We compared two recent thermal images acquired in 06/25/2015 and 07/22/2016 before and after logging operation respectively to show dynamic of temperature pattern in spatial and temporal scales. After downloading satellite images from USGS[1] website, in preprocessing step order to eliminate errors caused by atmospheric and radiance sensor and the atmosphere calibration by ENVI 5.0 software has been done, as next step by calibrated images and according to satellite imagery mapping metadata file constants the land surface temperature was investigated.

Results and Discussion

1 United States Geological Survey (https://www.usgs.gov)

In recent decades thermal pattern of a large region of Abadan Island has been changed clearly, a part of this change relates to man-made activities and another part belong to natural changes, important fact about this situation is natural changes affected by man-made activities indirectly. Javadzarin and Alavipanah (2016) investigated changes of thermal pattern during three decades in Abadan Island from 1985 to 2015 by satellite images of Landsat series, their results showed a big change belong to thermal pattern that caused by destruction of groves in this area.

Results of this research demonstrated there is an important different between these two patterns before and after logging operation, as different period of time, pattern of LST changed with regards to land use too, in other words we observed for same places before and after logging operation (variability of time) and according to land use (variability of location) a difference between 8 to 10 C^o (Figs 2 and 3). Most affected area of Minoo Island is southern lands.

Some of parameters of Minoo Island drainage and irrigation project like water requirement, drainage coefficient and its related variables (including depth and distance between open drainages and laterals) designed *before* logging operation and need to be revised, because water requirement and content of run-off in both irrigation and drainage systems of this project designed before logging operation and *after* cut downing more of 300,000 trees (mainly Tamarisk trees), pattern of LST and consequently rate of evapotranspiration changed deeply (Fig 4).

These results show importance of spatial and temporal changes of temperature and its role to effect on water requirement, especially in drainage and irrigation projects. Finally, authors recommend strongly application of TRS technology as an alternative for or at least a complementary method beside of traditional methods to estimation evapotranspiration by databases like NETWAT that is based on meteorological stations data provided as spot small scale.

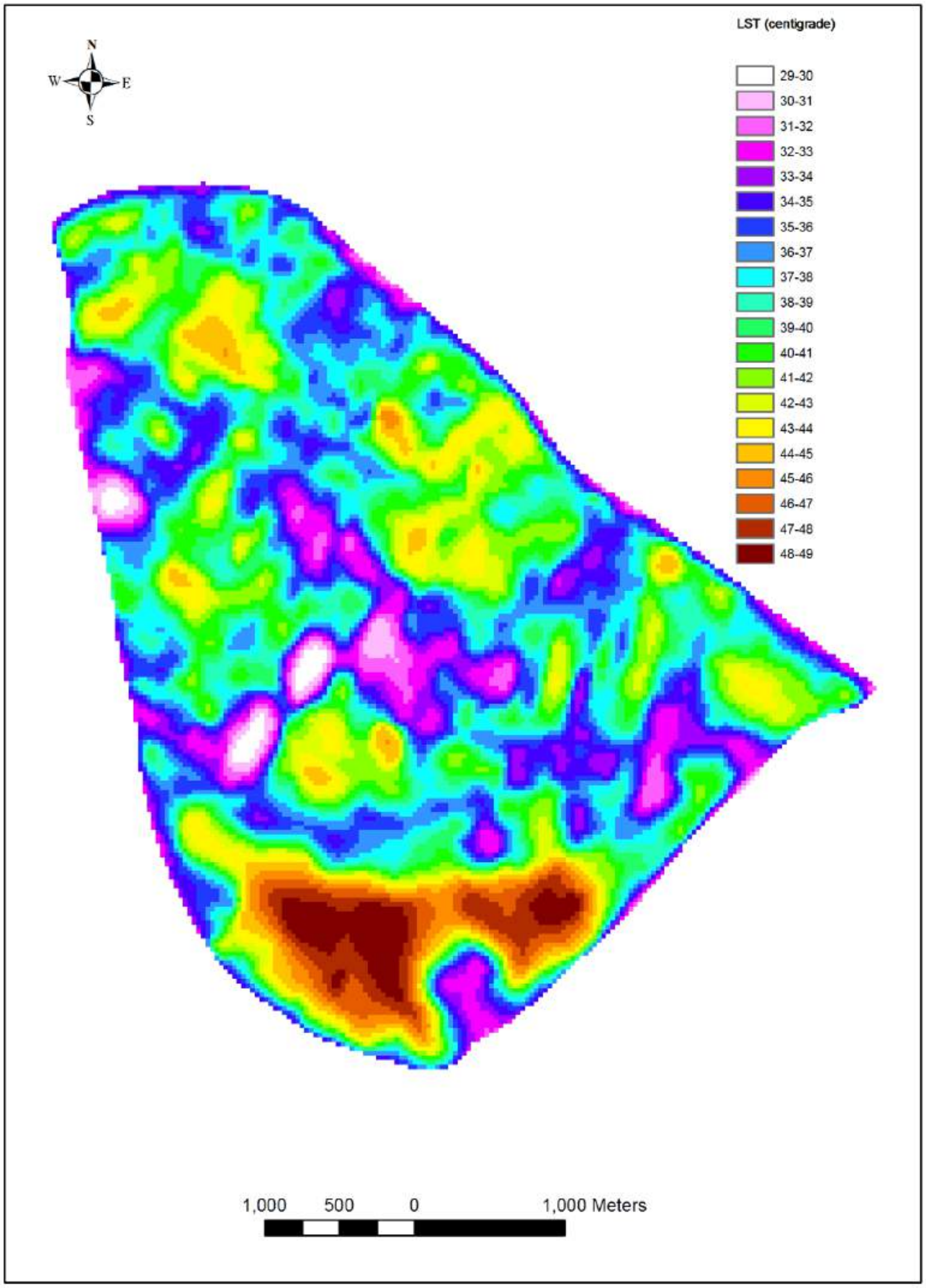

Fig 2: Spatial changes of Minoo Island LST (11 July 2015)

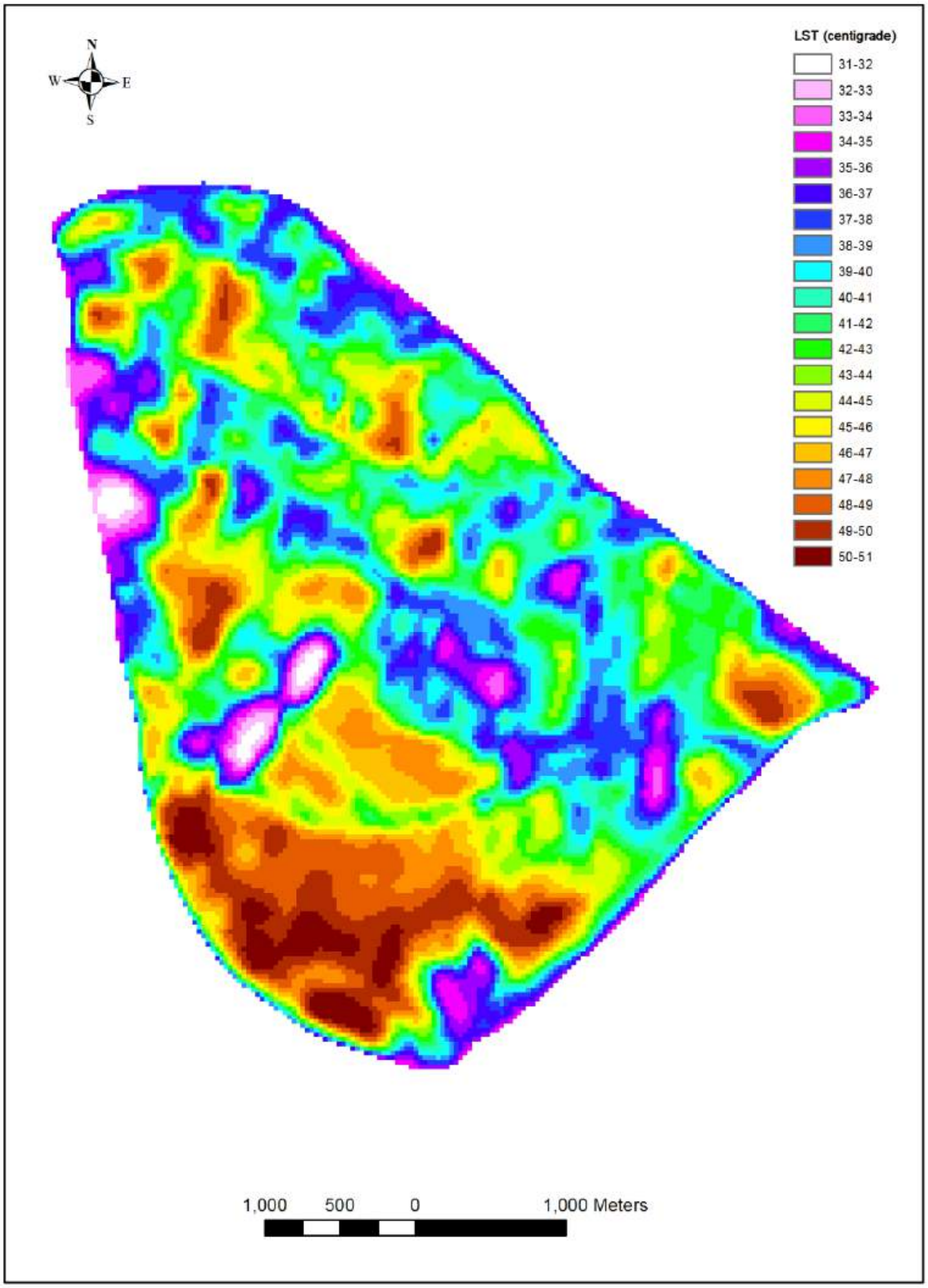

Fig 3: Spatial changes of Minoo Island LST (13 July 2016)

Fig 4: situation of vegetation Minoo Island before (left, 11 July 2015) and after (right, 13 July 2016) of logging operation

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CLIMATE CHANGE RESILIENT WATER MANAGEMENT MEASURES IN AGRICULTURE IN FINLAND

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Abstract

In Finland only about 15% of agricultural fields can be cultivated without drainage. About 58% of field areas have subsurface drains and 27% have ditch drains. The distance between the point of discharge of field drainage and the closest body of water is on average 2.3 km (median 1 km). Presently the drainage systems are utilized only in rare cases for wetlands and other elements to reduce nutrient flux and for balancing water flow.

In Nordic regions climate change will deteriorate in winter time weather conditions: snow cover has had a greatly reduced duration, and most of the precipitation is rain instead of snow. This has had repercussions for agriculture and drainage and their environmental impacts. Previously snow cover protected agricultural fields during winter from erosion and nutrient leakage. It has been already observed that agricultural fields have become more prone to erosion and consequently unprecedentedly high nutrient concentrations have been recorded in rivers downstream from agricultural areas after heavy rains and during a time when the fields have a small amount of vegetation cover. In addition the changes in the time and amount of precipitation has resulted into a need to change recommendations for the dimensioning of drainage systems.

Sustainable practices in drainage such as two-stage drainage channels, constructed in wetlands, sedimentation ponds and floodplains should become the standard practice in Finland in order to control the eutrophication problems caused by agricultural drainage. In order to reach this goal several social and political problems should be resolved. For example there is a need to reserve larger land areas for drainage. This is especially problematic when considering the EU's Common Agricultural Policies, which include agricultural subsidies paid to farmers per cultivated hectare – the farmers see it as being especially problematical if they have to give up farming area. Despite the social and political problems two-stage drainage channels have been implemented in few cases in Finland. Several good examples of the usage of wetlands, submerged dams and floodplains also exist. The paper reviews some of the examples and presents the environmental benefits of the solutions.

KEY WORDS: Two-stage drainage, Sustainable agriculture, Climate change, Finland.

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Introduction

Rethinking drainage

In Finnish agriculture effective drainage systems are the most important component of infrastructure. Without it agricultural production in the cold and rainy climate of the northern Europe would not be possible**.** While enabling agricultural production, the drainage systems have decreased the water holding capacity of watersheds, caused increased vulnerability to erosion if measures for erosion control are not utilized and also carbon leakage from organic soils. The general problem is that the drainage systems using traditional designs do not include elements which withhold flux of particulate matter.

In the Nordic areas effects of climate change will cause increases in erosion and in leakage of nutrients by year 2050. This will cause a higher eutrophication pressure of the aquatic systems especially in watersheds with high amount of agricultural areas. There is a potential for avoiding this scenario, if more environmentally friendly agricultural practices are used or if new practices are developed.

There is still an untapped potential in drainage systems with benefits for aquatic systems and biodiversity. Restructuring drainage would require changes in many subsidies, policies and even in attitudes towards water protection in agriculture.

History of environmental effects of agriculture and drainage in Finland

There has been a long road of development with water protection, as well as with environmentally friendly agricultural practices and their research (Vuorenmaa et al., 2002), (Tattari et al., 2016). At the same time agriculture has gone through fundamental changes.

In Finland drainage channels are privately owned. They are governed through communities of local landowners (drainage communities). State of Finland has been compensating for the costs related to drainage operations for several decades. Lately there has been a discussion, if the compensations are anymore justified.

Almost whole agricultural land area in Finland had basic drainage networks by the end of the 1960's. The drainage networks opened new straight and fast connections from agricultural fields to lakes and rivers. Traditional main ditches were designed to be straight, even and with steep sides – as efficient hydraulically as possible. This kind of basic drainage networks channel water efficiently away from fields, and offer no means for reducing the environmental impact of nutrient flux from agricultural fields to natural aquatic ecosystems (Puustinen et al., 1994).

Drainage depth was for a long time determined based on the depth which is most beneficial for cultivated plants (60-80 cm). Nowadays the depth is determined by the soil's load bearing capacity for heavy machinery (120-130 cm). Deepening of drainage depth has caused increased environmental impact from organic soils, as organic matter became vulnerable to erosion and degradation. Large areas of drained organic soils have since slowly turned to mineral soils. On mineral soils deeper drainage depth does not cause increases in environmental impact, if agricultural practices are otherwise sustainable.

Because of the increase in drainage depth and new connections between agricultural fields and natural aquatic ecosystems, water flow from agricultural fields to aquatic systems has become more variable than before i.e. the buffering capacity of drainage areas has decreased. This has been especially notable in watersheds where also forest areas have been drained.

Finnish agriculture has gone through a lot of changes on the long timescale. According to national statistics since the 1960's agricultural land area has decreased (from 2.7 million ha to 2.2 million ha), there has been a change from grassland farming to spring cereals (grassland area has decreased from 1.4 million ha to 0.6 million ha), fertilizer use has increased and mechanical tillage has become widespread. All this has been possible because of efficient drainage systems.

As drainage and agricultural practices became more efficient, also erosion and nutrient flux from agricultural fields has increased. Anthropogenic eutrophication of water systems originates mainly from agriculture (50% of nitrogen and 60% of phosphorus). After Finland joined the EU in 1995, several agricultural practices for reduction of water pollution have been implemented through agri-environmental schemes, which have been widely popular among farmers.

Despite the popularity of agri-environmental schemes, only slight reductions of phosphorus loading of water systems have been observed in agricultural areas and nitrogen pollution seems to have even increased. On the average water pollution caused by agriculture have remained on the same level as during the 1990's, around 15 kg-N ha^{-1} yr^{-1} and 1.1 kg-P ha^{-1} yr^{-1} (Vuorenmaa et al., 2002), (Tattari et al., 2016).

There have been several different views about reasons behind the low effectivity of agri-environmental practices. Suggested reasons have been for example changes in arable land area and centralization of non-cereal and animal farming (Aakkula and Leppänen, 2014). Another reason could be that the effects are masked by high variability in other anthropogenic and natural sources of nutrients.

Now the main problems are: how to prepare for impacts of climate change in drainage operations and in agri-environmental schemes, what kind of role drainage systems should have in future, and is it possible to reduce environmental impacts of agriculture through drainage practices. These problems are related to the following questions, which will be addressed in this article:

1) how widely should water protection measures for agriculture be implemented
2) what kind measures would improve the buffering capacity of catchments
3) can two-stage drainage systems improve the state of the environment.

This article will go through the history of development and the needs to improve water protection measures within Finnish agriculture, and how have we reached these conclusions.

Materials and methods

Hydrology – precipitation and runoff

Long-term (1960-2015) average precipitation in southern and southwestern Finland has been 700 mm (Table 1), of which 40% becomes runoff and about 60% evaporates. Typically during growth season evaporation is 120-130 mm larger than precipitation, causing a deficiency of water. The runoff during growth season is only 10% of total runoff during a year and the rest occurs outside growth season – during a time, when a large proportion of agricultural fields lack vegetation cover (tillage is usually done during autumn).

Majority of yearly runoff has typically, until the last few years, occurred during spring when snow cover melts off. Precipitation during autumn season is usually also high. The most relevant issue is, that the majority of runoff and fluxes of nutrients and particulate matter occur outside growth season, during only few weeks (when temperatures are above zero Celsius) (Puustinen et al., 2007), (Veijalainen, 2012).

Table 1. Average precipitation during a year (mm), average runoff during a year (mm) and proportion of seasonal runoff of the total annual runoff (%) during years 1961-1991 (statics of Finnish Meteorological Institute published in for example Vakkilainen 2009).

Region	Precipitation mm	Runoff during a year (mm) and proportion of seasonal runoff of the total annual runoff (%)				
		Year	Spring	Summer	Autumn	Winter
Southern Finland	700 <	300 - 400	45	10	25	20
Central Finland	600-700	< 300	50	15	25	10
Northern Finland	500 - 600	400 <	45	25	20	10

Runoff and agricultural drainage

Drainage water from agricultural fields flows on the surface, in subsurface drains and as groundwater. Several factors such as slope of fields, soil type and soil compaction influence the routes water flows take.

In Finland about 60% of arable land has subsurface drains. About 25% of agricultural plots have open ditches, and there drainage intensity is weaker. Only about 15% of arable land is cultivated without open or subsurface drainage. There is no significant difference in water pollution if fields are drained through subsurface or open drainage.

Basic drainages have typically dimensions to fit in floods which occur once every 20 years. However, the dimensions are calculated based on the climate conditions which have prevailed over the last decades.

Average distance between place of discharge from field drainage and inflow to closest natural aquatic system is 2.3 km (median 1.0 km). Especially during spring floods the delay between discharge from fields to receiving body of water is very short. This inevitably means that the buffering capacity of drainage areas is small and that drainage water have the same quality when inflowing to a body of water as they had when they were outflowing from agricultural fields (Puustinen et al., 1994).

Evaluation of water pollution levels - monitoring and models

Nutrient pollution from various sources has been monitored through water sampling for over 30 years in small catchments (Tattari et al., 2016). In addition particulate matter and nutrient fluxes have been researched at experimental setups for decades (Puustinen et al., 2010), (Uusi-Kämppä, 2010), (Turtola, 1999). The research and monitoring have given a good picture about the factors which influence the load on aquatic ecosystems.

In addition to field research, several internationally and nationally developed models have been introduced to practice. The most important ones are ICECREAM, INCA and SWAT models (Malve et al., 2016). For practical work in Finland VEMALA and RUSLE models are most commonly used (Lilja et al., 2016), (Huttunen et al., 2016). Additionally, a model based on experimental research was developed (VIHMA tool) (Puustinen et al., 2010). It can be used to estimate particulate matter and nutrient loading from agriculture on aquatic systems. The models and the data they are based on have been utilized for decades in estimation of environmental impact of agriculture and in designing agri-environmental schemes for reducing the impacts.

Up to last few years monitoring practice has been based on water sampling, but lately there is a move towards continuous water quality measurements. Continuous measurements enable acquiring better quality of data about flood situations and nutrient concentrations in discharge (Linjama et al., 2010). It has been observed that nutrient load on water systems is probably higher than previously has been assumed. The error has been caused by too infrequent water sampling, which has often missed the high discharges of water and nutrients which occur after heavy rains and snow-melt events (Figure 1).

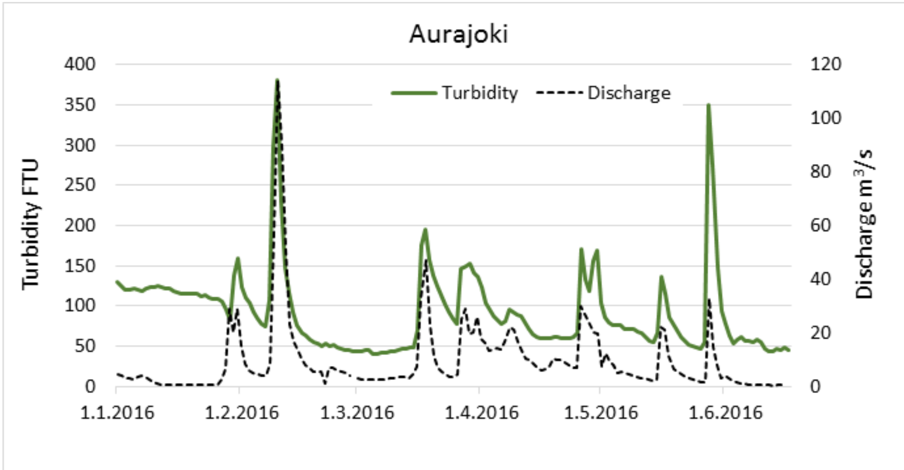

Figure 1 (Marjo Tarvainen, unpublished). Turbidity and discharge volume measured in Aurajoki with continuous water quality and quantity monitoring from January to June in 2016. If turbidity was estimated based on water sampling during the same period, conclusions could vary a lot based on timing of sampling.

Nutrient loading of aquatic systems

Many different point and diffuse sources cause nutrient loading on aquatic systems (Table 2). Notably, natural background loading is very large. Agriculture is clearly the largest source of anthropogenic nutrient pollution. On average agricultural nutrient pollution is 15 kg-N ha^{-1} yr^{-1} and 1.1 kg-P ha^{-1} yr^{-1} (Vuorenmaa et al., 2002), (Tattari et al., 2016).

Table 2. Average particulate matter and nutrient loading from various sources to aquatic systems. Here both diffuse and point source loading have anthropogenic origin.

Character of nutrient source	Particulate matter and nutrient load 1000 kg yr^{-1}		
	Particulate matter	Total phosphorus	Total nitrogen
Natural background flux	155 000	1500	39 500
Diffuse sources	1 621 600	3550	51000
○ *Agriculture*	1 340 000	2 400	33 000
Point sources	18 800	485	16334
Total	1 795 400	5 535	106 834

Agricultural particulate matter and nutrient loading to aquatic systems have been increasing since 1950-60 up to their present levels (Kauppi, 1984), (Rekolainen, 1989). During this time annual amounts of precipitation and runoff have remained stable. Increased nutrient loading to aquatic systems is thus caused by increases in the concentrations of nutrients in discharge. This is related to the many changes which have occurred in agriculture.

Notably, inter-annual variation in nutrient pollution to aquatic systems caused by hydrological climate conditions is very large and is clearly visible in monitoring results (Vuorenmaa et al 2002, Tattari et al 2016). In years with wet and mild winters agricultural loading is much larger than during years with dry and cold winters (Puustinen et al., 2007).

Since 1990's agricultural nutrient pollution to aquatic systems has remained constant. Small changes in arable land area have had no observable influence on the load (Vuorenmaa et al., 2002), (Tattari et al., 2016).

Management of discharge and nutrient fluxes in agriculture

Presently used measures targeted at preventing water pollution are: sustainable farming practices on the fields, vegetative buffer zones along the edges of fields and measures which are done outside of arable land area such as constructed wetlands. Their main goal is to decrease erosion, which will also reduce nutrient discharge.

Both sustainable farming practices and vegetative buffer zones are supported through EU's agri-environmental schemes programme. Since 1995 farms increasingly took part into the programme and at present about 90% of arable land area has joined it.

The effects of the programme were positive. As usage of mineral fertilizers decreased, also gross nutrients balance on arable land decreased by 35% for nitrogen and by 60% for phosphorus by year 2010. Land area ploughed during autumn decreased from 1.2-1.3 million hectares to 0.5 million hectares. Autumn tillage has been replaced with various forms of practices which have vegetative cover during winter: stubble cultivation 200 000 ha, spring tillage with stubble during winter 360 000 ha and direct sowing 156 000 ha. Area of established vegetative buffer zones is about 8000 ha and also a few hundreds of new constructed wetlands have been implemented (National agricultural statistics).

The systematic implementation of basic drainage network was a long term project, which was mostly finalised by the end of the 1970's. After that drainage projects have been mostly major overhauls or refurbishments. Overhauls are done based on the old designs and dimensions. Two-stage drainage or other sustainable solutions have not been implemented except for few exceptions.

Impacts of climate change on precipitation and discharge

In Finland the impacts of climate change will be most pronounced during winter - the winters will be much milder and will cause the Southern Finland to remain without a continuous snow cover through winter (Jylhä et al., 2008), (Olsson et al., 2015). Majority of precipitation during winter will be rainfall instead of snow. Later the same effects will occur also in Central Finland. The milder winters will lead to disappearance of typical spring floods, because there will no longer be a lot of snow melting away at once. Instead of continuous snow cover the snow will fall and melt away several times per winter. The same will happen for frost in soil. These changes will lead to high amount erosion and discharge of particulate matter and particulate phosphorus - even when the total amount of discharged drainage water would remain constant (Puustinen et al., 2007). If also the amount of precipitation will increase during winter, then the erosion rate and phosphorus flux to aquatic systems can be triple on agricultural fields without wintertime vegetative cover (Puustinen et al., 2007).

Results and conclusions

Effectiveness of agri-environmental schemes and management of water pollution

Even though changes in agricultural practices and in the amount of agri-environmental schemes taken into practice have been large, it was not observable in monitoring results of small catchments (Tattari et al., 2016). The effect of the agri-environmental schemes was estimated with VIHMA-model by comparing year 2010 with a year before Finland joined the EU (pre-1995): the schemes reduced the amount of particulate matter, nitrogen and phosphorus flux from agriculture to water systems by 16-22% (Table 3) (Puustinen unpublished). The estimation was done for years when hydrological climate conditions were average.

However, if the climatic change towards milder winters is taken into account (Table 3), the effect of the improved practices and agri-environmental schemes is significantly smaller. In practice, the improvement would be within the natural variation and not observable in monitoring results.

In Table 3 the listed estimates of effects from measures on the fields (implemented agri-environmental measures on arable land), riparian buffer zones, constructed wetlands (too few for statistical significance), total (total estimated effect of implemented measures in 2010 in hydrologically average years), mild winters (estimated effect of measures implemented on arable land in 2010, taking into account a change towards milder winters) and total potential (what could be achieved if measures were implemented more efficiently – taking into account change towards milder winters) are given for suspended solids (SS), particulate phosphorus (PP), dissolved reactive phosphorus (DRP), total phosphorus (TotP) and nitrate (NO_3-N).

Table 3. Impact of agri-environmental schemes on agricultural nutrient discharge to water systems (%), when comparing years 1990-94 to year 2010 (Puustinen unpublished). See text for further explanation.

Environmental measures	Change in agricultural nutrient discharge (%) at present amount of implemented measures and at different scenarios				
	Erosion (SS)	PP	DRP	TotP	NO_3-N
Measures on the fields	-22	-16	11	-6	-19
Riparian buffer zones	-2	-3	1	-2	-1
Constructed wetlands	-	-	-	-	-
Total	-24	-19	12	-8	-20
Mild winters	-9	-4	14	3	-10
Total potential	-32	-25	12	-13	-19

Similar preliminary results were obtained from ICECREAM and VEMALA models, which predict increase in phosphorus loading from arable land area by year 2050 (Figure 2) (Huttunen unpublished). These estimates show a variable change for different catchments in years 2020-29, because the base years (2005-2014) were already unusually warm and wet.

If all potential environmental measures were put into use, it would possible to reach big reductions in nutrient leakage from agriculture - if climate change was not happening. Because of that, in future Finland will need more efficient measures than are presently used - larger land area covered by present measures, better targeting to vulnerable areas, and also completely new measures (Silander et al., 2006), (Huttunen et al., 2015). Measures targeting soil and drainage have potential and will be a major focus in future.

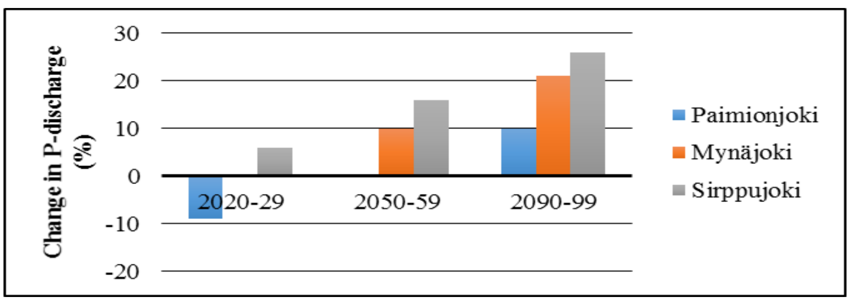

Figure 2. Preliminary estimation of impacts of climate change on phosphorus discharge from agriculture in three catchments in Southwestern Finland (Paimionjoki, Mynäjoki, Sirppujoki) in comparison to years 2005-14 (Huttunen unpublished). The phosphorus discharge will increase by year 2050, assuming the present level of agri-environmental practices. Results from ICECREAM and VEMALA models, using A1Bmean climate change scenario.

It is also possible that within few years continuous monitoring of water will improve the knowledge about nutrient fluxes from agriculture, as well as and will improve the understanding about the need for agri-environmental measures.

New measures targeting drainage

Several different arguments for implementing into wider practice the two-stage drainage have been presented: they are part of blue and green infrastructure in rural landscape, forming corridors for various species, improve biodiversity, and at the best case scenario bring back habitats which were lost when open field drainage was changed to subsurface drainage. They are one type of catchment scale agro-ecological solution (Wezel et al., 2016) with both water quality and ecological benefits.

In management of drainage water and nutrient loading an essential feature of catchments and drainage areas is buffering capacity: how much can different structures delay the flow of water without causing waterlogging or other problems. Two-stage drainage with channels for normal water and high water can easily be supplemented with sedimentation ponds and constructed wetlands. All of these structures can improve the buffering capacity.

The implementation of sustainable rural drainage systems should take place whenever a need for major overhaul occurs. It will be needed to estimate how much of the climate change impacts can be compensated with increasing the implementation of agri-environmental measures and how much with two-stage drainage. It is also needed to research: how important factor is buffering capacity or delay between point of discharge from a field and inflow to a body of water, how it influences nutrient loading and if the effect is comparable to constructed wetlands. Also the most environmentally efficient dimensioning of a two-stage drainage is still an open question.

A related question is how will climate change influence precipitation and how will it affect discharge. It will remain to be seen if disappearance of spring floods will cause more continuous discharge throughout winter. This could allow using smaller dimensions for ditches.

There are still several practical problems, which prohibit a wide use of two-stage ditch design. The problems are often related to agricultural subsidies and present agri-environmental schemes. Agricultural subsidies were not planned to allow easy cooperation between farms, which would be needed for reforming basic drainage networks. Despite these problems a few pilots of two-stage drainage has been carried out in Finland.

Functional principles of two-stage drainage

In contrast to several other agri-environmental methods, two-stage drainage channel’s main functional principle is based on flood situations (Figure 3). During floods water level rises until it reaches the flood plains, where speed of drainage water is slowed down and particulate matter can settle down on the flood plain. If the channel also includes constructed wetlands and wider areas of flood plains, then the efficiency of particulate matter removal is improved.

Environmental benefits of a two-stage drainage channel were estimated in a PhD-thesis published in 2016 (Västilä, 2016). According to the estimate up to 20% of particulate matter flux could settled on the flood plains of a 1 kilometre long two-stage ditch. Also the results suggested that vegetation should be kept quite short, so that it will not restrict water flow during flood events too much.

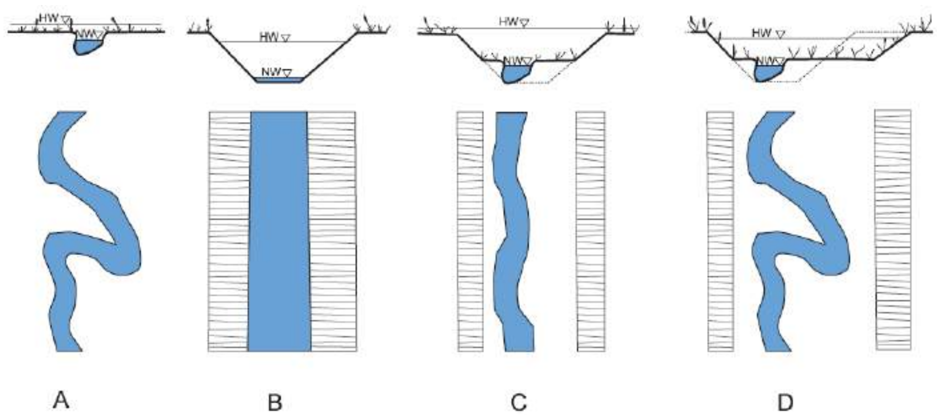

Figure 3. A) Natural brook, B) traditional main ditch, C) two-stage drainage channel, D) two-stage drainage channel after several years of operation.

Example 1: Ritobäcken

Ritobäcken is a small brook in Southern Finland. The brook is part of the Natura 2000-network, flows through agricultural area before discharging to a national park and is a habitat for a protected population of trout.

When a major overhaul of the part flowing through agricultural area became under evaluation, it was recommended that drainage depth should not be increased and the channels vulnerability to erosion should be especially considered. Because of these reasons a major overhaul using old designs and dimensions was considered to be not allowable.

In 2010 Ritobäcken was overhauled into a two-stage channel (Figure 4). Since then no maintenance has been needed, but now bushes are taking it over slowly. Now there is a need to plan how maintenance should be carried out – there is no previous experience with it in Finland.

Experience with the pilot showed that subsurface drains which discharge to a two-stage channel should be shortened, so that the drained water from fields is discharged on top of the flood plains. If sub drains continue below the flood plain, they will get blocked up very easily.

Figure 4 (Elsi Kauppinen). Two-stage channel at Ritobäcken six years after construction work.

Example 2: Leppioja

Leppioja is a ditch at a region with acid sulphate soils in Northern Finland. Because of the soil type, it is not allowed to increase drainage depth. However, the area had regular flooding on the fields during spring time. These reasons left as an only option to renovate the ditch to a two-stage drainage channel (Figure 5). Some sedimentation ponds and erosion control measures were also incorporated into the plan.

Figure 5 (Elsi Kauppinen). Two-stage drainage channel at Leppioja, a few years after construction work. Connections to subsurface drains for easier flushing are visible on the sides.

At Leppioja subdrains were cut short to end before the flood plains. This is especially valuable at this region, because at acid sulphate soils subdrains are very prone to becoming obstructed and have to be flushed once per year. The flood plain offers an easy access and working area for the drain flushing work.

Other experience gained at Leppioja was that at acid sulphate soil areas the renovation to a two-stage drainage channel should be carried out as one sided work whenever possible. Some parts of the channel still have no vegetation after few years, because the soil is too acid. If one side of the channel was left as it was, without construction work, it would limit the amount of erosion.

Example 3: Mättäänoja

Mättäänoja is a drainage ditch in southwestern Finland (Figure 7). It will hopefully be the first example of a two-stage channel in Finland, where the original idea came from land owners. The plans for the overhaul have been prepared, and at present the landowners are ready to apply for funding. The main goal is to make the area less prone for flooding. The area used to be a swamp, until it was drained for agricultural use. Slowly the organic soils have become more compacted and drainage depth has decreased (now less than 50 cm).

Figure 7 (Elsi Kauppinen). Mättäänoja-ditch in April 2016, before growth season. Low drainage depth is causing the fields to have regular flooding after snow melt and heavy rains.

Conclusions

Impacts of climate change in Finland will mainly cause environmental degradation. If we want to adapt to the changes and avoid the degradation, then water protection measures should be more efficient in future. Even though adoption of agri-environmental measures was large in scale, its impacts have been not been visible in water systems because the effects of climate change are already eroding away the potential positive results.

In 60's and 70's the state of Finland supported financially the construction of hundreds of thousands of hectares of basic drainage network. Nowadays still every year hundreds of hectares of major overhauls receive funding from the state. In comparison to these numbers, the total amount of established environmental measures within drainage network has been very low: few hundreds of hectares of constructed wetlands and a couple of examples of two-stage drainage channels.

There is a need to evaluate if governmental funding for drainage network overhauls should have more strict environmental standards, how sustainable drainage practices could become the norm and how is it possible to increase the buffering capacity of drainage areas. To solve these problems we still need to improve the possibilities for cooperation between farms by changing the agricultural subsidies. Drainage and blue/green infrastructure will be important aspects in adapting to climate change and in development of sustainability of practices in the future.

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WATER SUPPLY SYSTEM AND THE SUSTAINABILITY OF SMALLHOLDER IRRIGATION IN ZIMBABWE

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Abstract

Irrigation agriculture is critical in enhancing food security especially in Africa where the carrying capacities for most rain-fed agricultural systems have been surpassed. As a result, small shareholder irrigation schemes have been prioritized as a rural development model and have regained renewed attention from global and regional developmental bodies as a climate change adaptation measure. However, there is hardly any case of a successful small shareholder irrigation scheme in Africa as the majority of them have been unreliable and contributed very little to the host countries and the livelihoods of the farmers. The factors leading to the unsustainability of the irrigation scheme are not fully understood. The major objective of the study is to assess the impact of water supply in the sustainability of small shareholder irrigation schemes in the study area. The study targeted 8 irrigation schemes in Zimbabwe. A mixed research method was used and 316 randomly selected farmers were interviewed. Focus group discussion, key informant interviews and field observations were used to allow for the triangulation of information.

Unprecedented siltation of water bodies compounded with inequitable water sharing and poor catchment management was has threatened the sustainability of smallholder irrigation schemes yet interventions in the schemes did not prioritize the sand abstraction water pumping system. The Zimbabwe National Water Authority (ZINWA) as the water governing body proved to be inefficient and detached from the farmers. Farmers could not understand why they were compelled to pay for the water as 70% of them rated its service as poor. A combination of farmers' low productivity levels, debilitating dependency syndrome, ZINWA's poor service culture and political interference in water governance has affected farmers' ability and willingness to contribute towards water bills. There was poor in- field water management and some schemes were poorly designed as there was no consultation with the local people on the designing of the pumping systems. The majority of the schemes faced frequent pump breakdowns and farmers had no reserved funds for repairs and replacement investment.

KEY WORDS: Smallholder irrigation scheme, siltation, Water management, Replacement investment.

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Introduction

Globally, investments in irrigation have been an essential element in increasing food production to feed the ever-growing population (Mutambara et al., 2014). The World's irrigated land constitutes 19% of the land under cultivation and supplies 40% of the world's food requirements (Wiltshire et al., 2013). Irrigation is a possible adaptation strategy for agriculture to climate change and population pressure especially in Africa, where the population relying on farming has long surpassed the carrying capacity of many dryland agricultural systems (Kortenhorst et al., 2002; UNDP, 2012).Wiltshire et al., 2013; Maliwichi et al., 2012). Unfortunately, throughout Africa, there are hardly any cases of successful and sustainable farmer-managed smallholder irrigation schemes despite all efforts by different development agencies (World Bank, 2008). Irrigation development and rehabilitation interventions targeted towards the poor in the arid and semi-arid regions of Africa have not yielded expected results and the countries in these regions remain among the most disadvantaged in the world (Darkoh, 1992; Darkoh, 1998; Biggs et al., 2009; Magombeyi et al., 2012; UNDP, 2012). Most of the small-scale irrigation schemes have been associated with poor performance and little sustainability of the investment that seem to be locked in a 'build-neglect-rebuild syndrome', where the established scheme would have a time when they were neglected or non-functional and then get rehabilitated, only to be neglected again latter (Venot et al., 2013).

Small scale irrigation schemes have been prioritised as a rural development model by many developing countries in the past 5 decades, not only because they had higher returns on investment but also because they were found to be adaptable to the local farming systems (World Bank, 2008; Venot et al, 2013). Seventy percent of Zimbabwe's rural population live in Natural Regions III, IV and V where rainfall is erratic and unreliable, making rain-fed agriculture unreliable (FAO, 1997; Poulton et al., 2002). There is a direct positive correlation between Zimbabwe's agro ecological region and the prevalence of poverty in the country as shown in Table 1. (Poulton et al, 2002; Mutambara and Munodawafa, 2014). This correlation suggests that irrigation is the best way of alleviating poverty in the drought prone regions of Zimbabwe. Unfortunately, only 38% of Zimbabwe's smallholder irrigation schemes were functional in 2013, 40% in 2014 and 21% in 2015 (ZimVAC 2013; 2014 &2015).

Table 1. Poverty prevalence in Zimbabwe by agro-ecological zone. (Poulton et al., 2002).

Natural region	Prevalence of Poverty	Prevalence of extreme poverty
I	62.4	36.2
II	71.6	41.2
III	77.3	51.4
IV	81.6	57.2
V	79.5	55.7

In the face of climate change and chronic poverty in developing countries, investment in irrigation agriculture is getting renewed attention from world and regional development bodies (UNCSD, 2012; NEPAD, 2008; UNDP, 2012; WFP, 2010). Yet, the factors that have been affecting the sustainability of irrigation schemes are not well understood (Manzungu & van der Zaag, 1996; Chancellor, 2004).

Although Asia has a lot of literature covering the water supply systems of irrigation scheme and how farmers have been responding to the changing demand in the water supply and how the government, the private sector and the individual farmers have been reforming the water and energy sector connected to the water supply system (Vermillion, 1997; Monari, 2002; Kadigi et al, 2012; *Mukherji*, 2012; Mukherji et al, 2012; Bryan, 2013; Falcon, 2013; Mundra & Garg, 2013), there is limited literature on the water supply system of smallholder irrigation schemes in Zimbabwe (Makurira & Mugumo, 2010). The majority of available literature on the water systems in Zimbabwe focused on the causes and effects of water related disputes and how they were resolved (Mombeshora, 2003; Svubure et al., 2010). As yet, no significantly known research has focused on the entire water supply system of smallholder irrigation schemes. The green fuel/ethanol plant along the Save catchment was the new establishment that was commissioned around 2012 and little has been done to study the downstream effects of such a giant water user on the smallholder irrigation schemes. Although siltation has been studied previously little was done to show the effects of the unprecedented siltation levels especially along the biggest river across Zimbabwe, such as Save River on the production systems of smallholder irrigation scheme (Morton 2013; Ncube, 2013) and how the farmers and other stakeholders have been responding to such problems in the water supply system. Several reports have highlighted on the poor capacity of ZINWA and ZESA with regard to water supply in the urban areas (Svubure & Zawe, 2010; Mapira, 2011) but none of these has focused on the effects of the inefficiencies of these parastatals on the functionality of smallholder irrigation schemes. The water supply system for smallholder irrigation schemes is a dynamic sector and little research has been done to gain an understanding of the water challenges faced by the irrigation schemes in the light of the unprecedented siltation and changes in the water use patterns in Zimbabwe (Morton 2013; Ncube, 2013).

The major objective of the study is to assess the impact of water supply in the sustainability of irrigation schemes in the study area. In order to meet this objective, the study had the following research questions:

- To what extent does the farmers' access to irrigation water affect the sustainability of irrigation schemes in the study area?

-Is the water supply adequate and reliable?

-What is the state of water source and irrigation water delivery system?

-To what extent are the irrigation schemes affected by the upstream competing water uses?

Materials and methods

An integrated research approach involving the use of quantitative and qualitative methods was used in this study. Questionnaire survey, key informant interviews, FGDs (Focus Group Discussions) and observations were employed to allow for triangulation of information. A commitment to inter-disciplinarity is often seen as a necessary precondition for successful sustainability research, connecting people's time use patterns with their spatial and material footprints (Fahy & Rau, 2013).

Eight community small-scale irrigation schemes in the south-eastern low-veld and the Midlands province of Zimbabwe (Tsvovani, Dendere, and Rupangwana in Chiredzi district, Zuvarabuda and Vimbanayi in Chipinge district, Insukamini, Mutorahuku and Mambanjeni in Gweru district) were purposively selected for this study. The targeted irrigation schemes lie within the agro-ecological region V which receives very little rainfall (less than 400mm per year) and very high atmospheric temperatures, making the need for irrigation technology more critical in the area than any other region in Zimbabwe.

A simple random sampling method was used to select participating farmers through a self-weighting system or proportional representation whereby a scheme with more farmers had relatively more respondents that were selected for the questionnaire interview. Random samples were taken by assigning a number to each plot holder and using a random number table to generate the sample list. A total of 316 farmers were interviewed from the 8 irrigation schemes. Key informant interviews were conducted with the following stakeholders; 8 Irrigation Management Committees (IMC), 8 traditional leadership, 4 Agritex officers, 4 Department of Irrigation officers and 2 staff members from the Zimbabwe National Water authority (ZINWA). Eighty one (43 females and 38 males) farmers were interviewed in 8 Focus Group Discussions. Purposive sampling was used to determine the FGD participants. A farmer needed to be a member of the scheme in the 10 years preceding the day of the survey to participate in the FGDs. Field observations were carried out in the targeted irrigation schemes with the guidance of an observation checklist. Observations focused on the functionality of irrigation schemes, structures design system, land utilisation patterns, condition of distribution structures, erosion, siltation of rivers or water sources and canal, weed growth in the canal and on farm, water logging, irrigation practices and the state of perimeter fence.

Data from the questionnaire survey was processed in SPSS and was subjected to both descriptive and advanced statistical analysis. Qualitative data from FGDs and key informant interviews were analysed using the thematic framework analysis approach.

Experimental site layout

Over 77% of the farmers had periods of limited access to water and the differences by name of scheme was shown to be significant using Chi-square test (χ^2=1.027, df=7, p=0.000 with 100% of the farmers in Vimbanayi and Zuvarabuda (Figure 1) reporting that they had periods in the year when they had limited access to irrigation water.

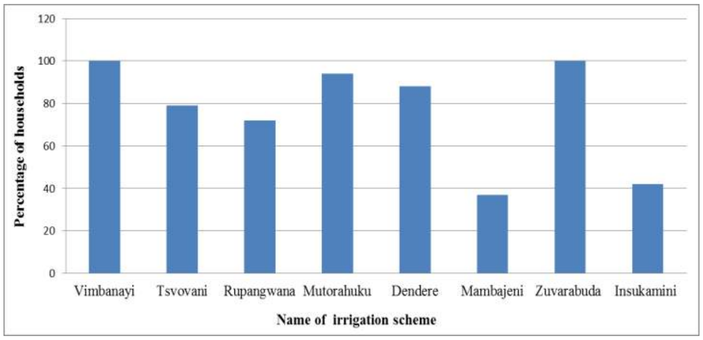

Figure 1. Percentage of farmers experiencing periods of limited access to irrigation water

The challenges farmers faced in accessing irrigation include siltation, selfish upstream users, pump breakdowns, poor water management, poor design of the water supply system and poor water system infrastructure as shown in Table .2. These challenges were discussed in depth in the subsequent section.

Table 2. Percentage of farmers facing water supply challenges in the different schemes

Water supply challenges	Vimbanayi	Tsvovani	Rupangwana	Mutorahuku	Dendere	Mambanjeni	Zuvarabuda	Insuka mini	Total
Siltation of water source	93	85	88	38	94	59	97	0	70
Damage of the delivery canal	0	10	0	85	0	0	0	0	11
Lack of night water storage	17	0	13	0	19	0	0	0	6
Low water level during critical times	42	42	0	59	41	0	61	0	31
Selfish upstream water users	80	83	109	0	94	0	73	0	56
Poor water management	20	75	0	68	13	0	0	5	24
Poor design	8	42	0	0	41	50	24	0	20
Pump breakdown	37	10	0	0	56	100	39	0	29

Siltation

Siltation of the water source was the major reason cited by 70% the respondents for having less water from the water source. All the schemes that had Save River as their water sources had problems of siltation. Field observations made during the survey and during the time when the researcher was working in the low veld of Chipinge and Chiredzi between 2008 and 2013 revealed that the problem of siltation was mainly felt during the dry season between September and December every year. The water would stop flowing; exposing the heaps of sand in the lower parts of Save River with a wide sea of sand platform dissected into tracks of shallow water strips running parallel each other as shown in Figure 2 and 3. According to the farmers interviewed, in Chipinge and Chiredzi, water related conflicts tended to be more prevalent during the dry season as the normal watering schedule became difficult to maintain. One farmer in Rupangwana said; "September to December ndiyo nguva inonetsana vanhu nenyaya yemvura muno. Zuva rinenge richipisa apa mvura yacho inenge yave shoma. Vanhu vanoita kunge vachatemana". (September to December is the time when people fight for water in the scheme as it will be difficult to maintain our normal irrigation schedule due to high temperatures and limited water in the river).

Figure 2. Save River with a small stream navigating through heaps of sand deposits near Rupangwana irrigation scheme

Figure 3. Save River- a week after the onset of rains in November 2014 showing high level of siltation

In Rupangwana, the farmers reported that they would concentrate on 2 blocks during the dry season and get back to their fields when the water situation normalised after the onset of the rainy season. This strategy involved each farmer cultivating less than 0.1 hectare during the period of limited access to water. In Dendere, the night storage was 2500 cubic metres and the 75 hectare scheme was divided into 5 blocks but only 4 blocks were used as the fifth one could not be used due to water shortage. Each farmer was allocated a 0.1 hectare field in each block to make sure that some farmers were not disadvantaged as some blocks were not accessing adequate water. Farmers from Chiredzi and Chipinge felt that the silts that were sucked by the water pump were affecting the normal functionality of the schemes. In Dendere one IMC committee member said, "We started experiencing more frequent pump breakdown the time when we started having a lot of silts on our side of the river and when we took out pump for service, the mechanic said that the sand was damaging the pump's impeller as it was increasing the pumping load of the pump". It was also confirmed by farmers in Tsvovani irrigation scheme, that before a new set of pumps was bought, more pump breakdowns were experienced during the dry season when the water discharge was low and sand would be closer to the pumps. Siltation also added the scope of work for the farmers as it required backbreaking scooping. In the case of Tsvovani, the sand that was sucked in by the pumps was deposited in the main delivery canal or the first reservoir and the farmers would scoop both ends, the suction point at the river and from the delivery canals. If allowed to accumulate in the canals, the silts from Save River would not only lead to the siltation of night storage dams but would also reduce the water holding capacity of the delivery canals leading to water spillage. In Zuvarabuda, the farmers had the extra responsibility of diverting the water that was usually prevented from flowing along the Chipinge bank side by the silts so that the water would flow near the suction point of the pump for the scheme. Each time the farmers were irrigating, they would use their shovels to direct the water to their pumping pool, scooping sand in the process. One farmer said; "Tinombobvisa zvedu ivhu nemafoshoro asi ibasa rinoda dozer kuti mvura iuye kuside kwedu, mavhu acho awandisa" (Although we do scooping using our own shovel, the work requires some earth moving machinery like dozers to direct the water to the side of the pump as the mass of sand to be moved is just too much). Farmers for Mutorahuku irrigation scheme reported that the scheme was severely affected by the reduction in the water level as it reduced the pressure needed to allow the syphoning system to suck water from the dam following vandalism of the original system that used to drain water from underneath. Initially, the system was designed in such a manner that an underground pipe would drain water from the bottom of the dam to the delivery canal. In the 2005 drought, the water level for the dam was so low that the whole dam was reduced to a small pool around the suction point. The illegal fish mongers who were taking advantage of the reduced dam water level to fish in the dam blocked the suction pipe to prevent fish from hiding in the pipe. By the time they learnt about the blockage, it was already too late to rectify it as the suction point was at the deepest end of the dam, making it inaccessible. The service of sea divers was needed to remove the stones that closed pipe. However, ZINWA reportedly, could not enlist the service of sea divers due to financial constraints. The farmers were told that sea divers were very expensive to hire. Instead, they inserted a syphonage system (see Figure 4 and 5) that played a similar role but only when the dam level was above 70%. Consequently, the system only works until August every year when the dam level would still be high. The moment the water level fell below 70% full, the reduced volume of water from the dam would not give the needed pressure build-up to force the water to be siphoned through the pipe. The poor water abstraction at Mutorahuku was preventing farmers from growing wheat in winter as the water supply could not irrigate the crop to maturity, considering that the dam would be below 70% full by August every year, when the wheat crop would still be in its late vegetative stage.

Figure 4. Mutorahuku irrigation scheme-showing the gravity powered system from the dam to the irrigation plots

Figure 5. The syphoning system of water abstraction at Mutorahuku dam in Sept. 2014

At Insukamini, farmers get their water from Insukamini Dam through gravity. The dam was constructed across Ngamo River, and was believed to be so big that, even if the catchment of the dam failed to receive any single drop of rain in 5 years, farmers would continue to irrigate in the scheme. Unfortunately, one of the dam's outlet pipes developed a small leak by the end of 2013, which was manageable in the first few days. With time, the leak grew bigger and became unmanageable (See position of the leakage in Figure 6). By the time of the survey, the ZINWA official based on the site indicated that the water that was coming out of the leaking pipe was more than what the farmers were using in the irrigation scheme.

Figure 6. Insukamini leaking dam wall

The farmers' fear was that, at that rate of water loss, the water in the dam would be finished before their crops reached maturity stage during the last week of November 2014. Unfortunately, ZINWA was taking time to rectify the problem, to tame the unaccounted for water losses and the ever increasing pipe leak which the ZINWA official based at the dam and the farmers believed could threaten the dam wall. As was the case with Mutorahuku, sea divers were needed to search for the rod that was used to close the gate valve located at the deepest inner side of the dam. It was a very dangerous spot and only sea divers could assist. Farmers were told that ZINWA had no money to enlist the service of sea divers. Since the leaking started, engineers from ZINWA never visited the site to weigh different options of solving the problem or to share with the farmers what they should brace for in the face of the new challenge. Farmers were never made aware of the estimated cost of hiring sea divers. For farmers who have been paying their water bills for almost 2 decades, they could not understand why ZINWA was failing to secure money to stop the leaking dam. This possibly explains why 74% of the farmers felt ZINWA's service was poor. Investigations by the researcher on the cost and procedure of getting the sea divers further exposed ZINWA's appalling lack of service delivery culture and commitment. The sea divers were found at the Police's Sub Aqua unit based at the Zimbabwe Republic Police Morris Depot in Harare. One needs to pay US$500 consultation fee and pay their subsistence allowance of $100 per day for every member of the team, which for a team of 5 divers could cost $500 per day. If the job takes 2 days, the service requester would just pay the subsistence allowance for the divers, giving a cumulative total of $1500. ZINWA's claim that they could not afford the service of the sea divers raised 2 issues. One being that they never bothered to inquire about the cost in the first place as it was cheaper than the syphoning system they introduced at Mutorahuku. The other issue is that ZINWA was so detached from the problems of the farmers that they never bothered to weigh the cost and benefits of the new system at Mutorahuku.

Competition with upstream water users

The Save River siltation, causing water shortage in smallholder irrigation scheme on the lower Save catchment during the period between August and December, was exacerbated by the fact that Macdom Sugar Estate, which feed into the Chisumbanje Ethanol plant usually block the whole river during the same period, to create a dam around their pump house (See picture in Figure 7 and 8). The water would only escape the barricades as seepage underneath the sand. The blocking of the whole river was done at the expense of the smallholder community irrigation schemes downstream at a time when the temperatures would be very high and the need for irrigation would be very critical in the schemes. Farmers in all the schemes expressed that reduced water discharge became more serious from the time Macdom resumed agricultural operations in 2009.

Figure 7. The Save River blocked to create a pool around the Macdom pump house

Figure 8. The Save River completely blocked at the Macdom pump house a week after the onset of the rainy season in November 2014

What disappointed farmers most about the water sharing violation by Macdom was the fact that ZINWA was not doing anything about the monopolisation of Macdom over the river water, although they had water permits allowing them to access water freely from the Save River. ZINWA had assured them access to irrigation water throughout the year even during the years of drought as ZINWA would open water from Osborne Dam in the upper Save Catchment. Contrary to their expectations, the water permits were not adding any value as they did not experience any improvement in water access after obtaining the water permits and paying up their water bills. Although several complaints were sent to ZINWA over this mal-practice by Macdom, nothing was done. The failure by ZINWA to enforce such a critical section of the Water Act, in the eyes of the smallholder farmers, showed that it could not support its founding principles. After failing to act decisively on Macdom to share the water equitably, ZINWA was pressing harder on the smallholder farmers to pay their monthly water bills, yet the farmers would have struggled through scooping to access the water. One farmer in Rupangwana said;

"Iyo mvura yatinenge tatambudzikira tichibvisira mavhu, ndiyo yavanouyira pano kuti pengera kuti tibhadhare. Apa vanorega ve Macdom vachitora mvura yese, dei vachichi piwa mari yacho ne Macdom yacho iyoyo" (we struggle to get our water through scooping and ZINWA comes hard on us to pay for the very water that we struggled to get. If they give priority to Macdom, why don't they get all the money from Macdom?).

Poor infield water management practices

Poor infield water management in the schemes was threatening their sustainability. For schemes like Insukamini, farmers started experiencing water shortages when the government extended the scheme using funds from the European Union. The extension of the scheme was done without the consultation of the farmers which in turn reinforced the farmers' perception that the scheme belonged to the Government. It was also done without due consideration of the water supply needs especially the enlargement of the main delivery canal from Insukamini dam. In Tsvovani, the in-field earth canals were in poor working conditions causing a lot of the pumped water to be wasted before getting into the field. The scheme was operating on earth canals since 1984, which were initially rammed but the canals were no longer in good shape. Some parts of the canal system had become so shallow, due to the accumulation of sediments, that the water could no longer take one direction causing leakages all over. Some parts were engulfed by grass that was curtailing the smooth movement of water as shown in Figure 9.

Figure 9. Shallow and grass choked canals at Tsvovani irrigation scheme

Consequently, some fields in the south eastern part of the scheme were failing to access water at all while water was taking a very long time to reach other parts, which challenged the water sharing system amongst the farmers. The poor state of earth canals was therefore causing water logging on some parts of the plots while other parts were completely dry. The farmers were not able to upgrade the earth canals into concrete canals as they were heavily saddled by water and electricity bills. Only those farmers whose plots were being affected by the siltation of the earth canal felt the urgency of repairing or clearing the canal while those served with concrete canals were not worried about the problem. However, the poor flow of water was affecting every farmer, as it was contributing to high electricity bills to the scheme. In Vimbanayi and Mutorahuku, field observations indicated that the embankments of the canals were so heavily eroded that it was a matter of time before they could collapse as shown in Figure 10. Some of the eroded canals had already started leaking. This level of neglect of the critical infrastructure in the schemes raised questions on the commitment of the farmers to the irrigation schemes. The filling of embankments did not require any special resource but importation of sand from one part of the scheme or just outside the scheme to the canal bank using wheelbarrows or buckets.

Figure 10. Eroded canal embankments in Vimbanayi and Mutorahuku schemes

Inability to pump during the rainy season

The researcher' experience along the lower Save river and farmers' reports confirmed that, in a normal or above normal rainy season, the Save River would be flooded from late December up to February. Because their plinths for the pumps were built on the river bank (Figure 11), they would be completely covered by water. In order to save the pump, farmers in Vimbanayi and Zuvarabuda would remove the pump and keep it outside the water until the floods subsided to safe levels.

Figure 11. Pump plinth for Vimbanayi & Zuvarabuda constructed near the river bank

The pumping unit at Zuvarabuda and Vimbanayi were mounted on wheels to allow the farmers to drag the pump off the river before the pump was inundated with the floods. This was an effective way of protecting the pump from the floods but the process was not thought through to cater for irrigation needs during flood times. Reportedly, the flooding of Save River was highly unpredictable because the water that floods this part of the river usually come from the high rainfall receiving areas on the upper course of the Save river. The floods usually happen when the area, being a low rainfall area, would be completely dry and their crops in the scheme are in critical need for water. Farmers indicated that if they were consulted by the engineer on the maximum extent of the flood under normal and extreme flood conditions, they would have helped to site the plinth using their local knowledge about the flooding pattern of the river. Considering that these schemes would have experienced water shortages between September and December due to the combination of siltation and the poor water sharing system with Macdom Sugarcane Estate, the farmers in these two schemes would only be left with 6 months or two cropping cycle of effective irrigation of their plots. Considering the poor level of productivity of the schemes, these two cropping cycles could do little to leverage the continued existence of the scheme in the face of high electricity and water bills. In Mambanjeni, the pump house was constructed near the bank of the Gweru river (see Figure 12) which usually got inundated with water every year and the farmers indicated that if they were involved in the siting of the pump house, they would have helped to avoid this design error to save the pump as all community members were aware of the extent of the flood of the river in a normal rain season.

Figure 12 Plinth and pump house at Mambanjeni built on the river bank

Pump breakdown

Pump breakdown was a major problem in the history of all the pumped schemes although their severity differed across the schemes in the 10 years preceding the survey. Vimbanayi and Zuvarabuda had almost similar experiences in pump breakdowns and how the problems were fixed. Their pumps were washed away by the cyclone and flood of the year 2000 and they were only fixed between 2008 and 2010 by Mercy Corps (NGO). At the time of the survey, moderate pump breakdowns were reported in Dendere, Vimbanayi and Zuvarabuda and Rupangwana. Tsvovani had never experienced any breakdown since the pump was fixed in 2009 by an NGO called Parsel while Mambanjeni was under breakdown by the time of the survey. For Dendere, the long history of breakdowns (since 1997) and how the farmers tried to fix the problem on their own explained how the number of farmers was reduced from 90 to around 50. In Dendere, farmers who participated in the FGDs recounted farmers' participation in the establishment and rehabilitation of the scheme which made them more committed to their scheme than the other schemes. During the year when they were handed over the scheme by of RED Barna (an NGO that helped to establish the scheme), they experienced a pump break down. The farmers had to contribute US$500 for the repair of the pump and those who failed to contribute towards the repair of the pump lost their membership to the scheme. This saw the scheme membership dropping from 96 farmers to 54 farmers. After frequent breakdowns, farmers resolved to buy two new sets of pumps in 2007, with each farmer contributing 100 Rands. The membership shrunk further to the current number of 38 farmers in 2007 after the other members failed to raise the 100 Rands needed for the replacement of the old pumps. The plots sizes were originally 0.18ha but had since increased to at least 0.4ha. In Tsvovani, the sand abstraction pumping system that was damaged by the cyclone and floods in 2000 was never repaired. What was left of it got vandalised during the 7 years of disrepair (between 2002 and 2009), to the extent that by the time of the survey, there was nothing left but a few remnants dumped outside the pump house as shown in Figure 13. In Rupangwana, when the sand abstraction system was damaged, ZINWA as the hitherto custodian of the pumps collected the pumps and its accessories for repair in Mutare in 2003. They never returned the pump. Reports of water pumps being taken away from the schemes by ZINWA or ZINWA related officials were not uncommon in schemes previously run by ZINWA. At St Joseph Irrigation scheme 20km from Dendere along Save River, the Chiredzi side, farmers lost their pumps under similar circumstances in 2004. In Rupangwna, a robust pump was allegedly stolen by ZINWA officials during the time when the Department of Water was transitioning to ZINWA.

Figure 13 Part of the remains of the sand abstraction system equipment at Tsvovani

Challenges in pump repair

All the 8 schemes had no member in their respective schemes that could repair pumps in case of breakdown, and mechanics for the repairs were only found in the towns of Chiredzi, Gweru, Bulawayo and Harare. The spare parts were either obtainable in Chiredzi or in Harare (about 600 kilometres away). The long distances travelled made these spare parts very expensive due to transport costs and the time to travel also increased the down-time periods of the pumps.

Only 31% of the farmers reported that they were contributing towards pump repair (Figure 14). The difference by sex of the number of farmers who were contributing towards pump repair was not statistically significant (χ^2=0.122, df=1, p=0.727).

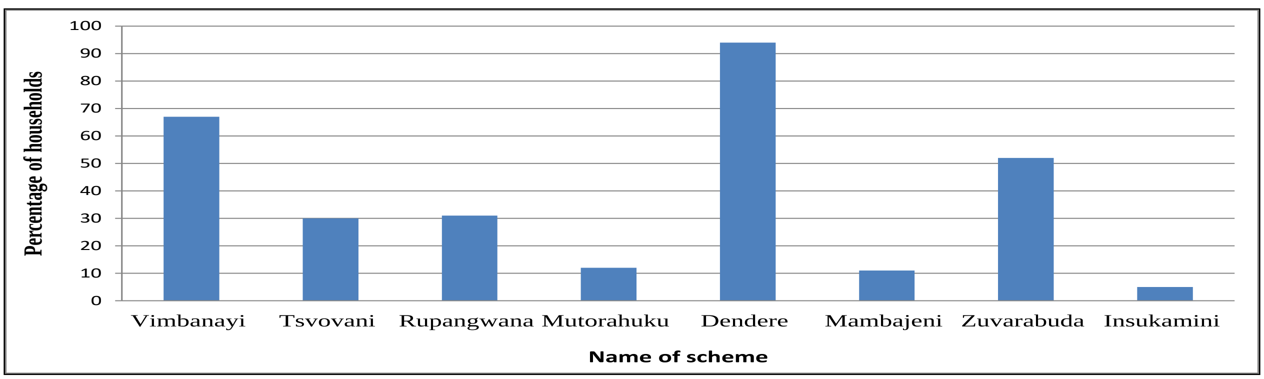

Figure 14 Percentage of farmers contributing towards pump repairs

The only reason farmers gave for not contributing towards repair was lack of money due to poor productivity levels. Sugar bean was the major cash crop for the scheme and the revenue received from the quantity of beans sold was regressed against the amount contributed towards pump repairs. Those producing more beans in the schemes were contributing more towards repairs as the regression analysis shows a positive linear relationship between the quantities of beans sold and the amount contributed towards pump repair R^2 = . 0.304, F=137.13 = 42.64, p < .001. The Pearson's correlation also show that there was a strong positive correlation between the quantities of sugar beans sold and amount contributed towards scheme repairs (r = .0.55, df=1 p =.001). This finding suggests that those who were selling more had a greater incentive to contribute towards pump repair than who were selling less. The Chi square tests revealed that there was a significant difference between farmers with different ownership perception of their irrigation schemes and the amount they were contributing towards scheme repair (χ^2= 217.22, df=1, p=0.000). Those who felt did not own the irrigation plot were contributing less money towards repairs, suggesting that, insecure land tenure was removing the incentive to contribute towards repairs of the scheme. It was also observed in the field that some of the pumps in the smallholder irrigations had outlived their design life and had became obsolete. Interviews with Department of Irrigation (DOI) officials hinted that if the farmers were made to invest in the replacement of these pumps in the preceding 2 decades, farmers could have bought new pumps on their own to replace old ones, instead of relying on Government or NGOs. Owing to the fact that the companies that used to deal in water pumps had closed down in the face of hyper-inflation and the country's economic melt-down, the DOI officials said that they were assisting individual farmers in buying new water pumps from South Africa where they were much cheaper than in Zimbabwe. For example officials from the DOI revealed that, whereas big pumps cost US$9000 in South Africa they cost between US$16000 and US$20000 in Zimbabwe. Unfortunately, it was also reported by DOI officials that these irrigation equipment (including irrigation pipes and drip lines) were still attracting import duty and taxes at borders making these critical equipment very expensive and unaffordable for most of the smallholder farmers in Zimbabwe.

Poor service provision by ZINWA

All the 8 irrigation schemes had water permits although they reported that their level of engagement with ZINWA was not adding any value to their operations as it was not translating into improved access to water. The service ZINWA was offering was rated poor by 70% of the farmers (Figure 15) and the difference in the farmers' rating across the 8 schemes was found to be statistically significant (χ^2=1.174, df=21, p=0.000). Mambanjeni had the highest proportion of farmers (91%) who rated the service poor, while Mutorahuku had the lowest proportion of farmers (26%) who rated ZINWA services poor. There was a significant difference on the amount contributed toward water bill and among farmers with different perceptions about the ZINWA service (χ^2=162.48, df =9, p=0.000) with those who rated it poor having the highest proportion of farmers who were not contributing anything towards water bills.

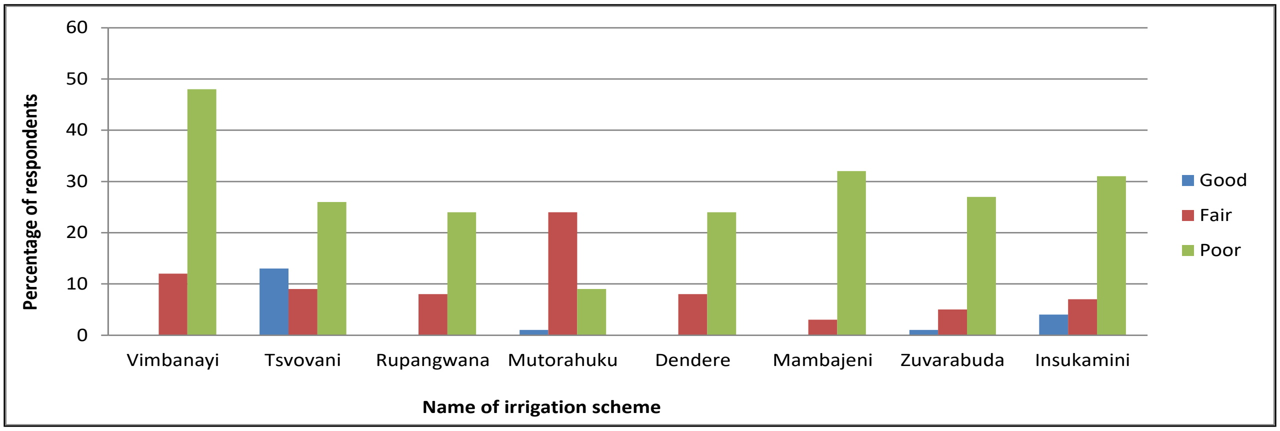

Figure 15 Farmers' rating of ZINWA service

This pattern suggests that farmers were resisting payment towards water bill due to poor service. Key informant interviews with officials from ZINWA confirmed that the organisation was getting resistance from farmers. One engineer from the Save catchment revealed that ZINWA was owed over US$35 million dollars by irrigating farmers across the country excluding those farmers who were irrigating illegally without the water permits. Farmers across the 8 schemes reported that they were no longer committed to clear off their arrears with ZINWA but were just paying enough money to prevent them from getting disconnected to water supply as they were not satisfied with the service from ZINWA.

Unjustified water charges

Farmers across the 8 schemes could not understand why they were compelled to pay for water irrigation from rivers and dam when there was no materiality in the service being offered by ZINWA. Unlike the farmers in Gweru district where ZINWA was actively involved in pump repair (at Mambanjeni), managing and running the gravity powered water system at Insukamini and Mutorahuku, farmers in Chiredzi and Chipinge could not understand why they were asked to pay ZINWA. They were extracting their water from the Save River and felt there was no apparent value addition in the involvement of ZINWA in their water supply system. One farmer from Zuvarabuda said; “Ndinorwadziwa ne ZINWA, Mari yatinobhadhara ndeyei” (I am particularly pained by the money that we pay to ZINWA, what is it for?). The farmers that participated in the FGDs confirmed that they were not getting any service from ZINWA. They felt ZINWA’s work was merely travelling to the scheme to collect their money every month and to disconnect the water supply if farmers failed to pay. If asked to attend to a pump breakdown or for any technical assistance, ZINWA would, according to the interviewed farmers, charge the farmer for both the mileage and for the repairs, making their service more expensive than that of private mechanics in Chiredzi. The justification that farmers were given by ZINWA for paying for water was that it was their legal obligation by virtue of The Water Act and The ZINWA Act as bulk users of water. Failure of which could attract a fine or imprisonment. The Water Act (Chapter 20:24), Sections 34 and 39, and The ZINWA Act (Chapter 20:25) Section 30, made it clear that anyone using water for commercial purposes should do so in terms of a permit issued by the relevant Catchment Council or an agreement entered into with ZINWA, and should pay (ZINWA, 2014).

The justification given by ZINWA officials was that the government had invested in dams and was set to recover some money from the investment in keeping with the 'User Pays Principle'. The Government was also expecting ZINWA to be independent in covering some of its running cost and not to depend on the fiscus. Also the dams from which some of the schemes were getting their water were managed by ZINWA and the operational costs and personnel costs attached to it had to be paid by the users as the Government was incrementally failing to cushion ZINWA.

Overcharging of farmers by ZINWA

Although the ZINWA Act requires that irrigating farmers have meters or other measuring devices at their points of abstraction for both billing and statistical reasons, none of the 8 schemes had meters to quantify the water used and charged for by each. The bill was therefore based on the projected water use per hectare and the pumping capacity of the pumps. For schemes like Dendere where the pumps were mal-functional, farmers felt these estimates were not a true reflection of the water consumption of the schemes. Also, crops at different stages of growth have different water requirements and the use of estimates was not smart enough to reflect such fluctuations in water demand. When the Save River was flooded and during times when farmers used less water due to low river discharge, ZINWA would continue to charge the same flat rate. That partly explains why farmers felt the ZINWA billing system was not fair.

In Insukamini, it was reported that ZINWA overcharged farmers during the early days of the introduction of multiple currencies in 2011/2012. The error emanated from the use of a much bigger hectarage than what the farmers were cultivating. By the time of the survey, Insukamini farmers owed ZINWA US$10 000. All the farmers were paying between US200 and US$400 per month towards the water bill. The error was never rectified and the farmers were struggling to service the debt with their own production. Farmers consulted the ZINWA office to get clarification over bills but no feedback was obtained. Each time they visited ZINWA they would meet a different person who knew nothing about previous reports on the matter. The catchment staff, based in Bulawayo (over 200 kilometres away), never visited farmers to talk about their problems and the person they usually met was the official responsible for collection of monthly payments towards the bill and who, when asked about the problem, always said; "ini ndavinga mari handina hurukuru, kana muchida hurukuru endai kwaBulawayo" (I have just come to collect money and if you have queries regarding the bill you should visit the catchment office in Bulawayo).

Political interference

ZINWA officials indicated that the institution's operations in dealing with all categories of farmers were affected by political interference. Without necessarily referring to smallholder farmers, they indicated that defaulters of payments for water permits were usually protected against disconnection by politicians, with indications that although they use disconnection as a strategy to force farmers to pay, an order by a politician to stop the process usually frustrates the efforts. They also highlighted that most ministers and high-ranking officials owed ZINWA millions of dollars and the institution could not do anything to them. The zenith of political interference was demonstrated in July 2013 when the Government ordered ZINWA and ZESA to cancel all the debts owed by rural and urban residents.

Rigidities in operations of ZINWA

ZINWA was using catchment boundaries rather than the political boundaries respected by other institutions. For some water users, this system of defining jurisdictional areas was proving to be very costly as that would entail travelling very long distances to get a service that could be offered by the same organisation closer by, but belonging to a different catchment. For example, although closer to the Sanyati catchment (20 kilometres in Gweru), Mambanjeni and Insukamini Irrigation schemes were working with ZINWA Gwayi Catchment with offices Bulawayo in Bulawayo, over 200 kilometres away. Such rigid adherence to catchment boundaries was expensive to both the farmers and ZINWA itself and one would wonder why ZINWA could not make a discretional decision to allow users closer to a ZINWA office to use it even if it did not belong to that catchment. That possibly explains why Mambanjeni had the highest proportion of farmers who rated the service of ZINWA as poor. Mutorahuku is in the same district as Mambanjeni which was serviced by the Sanyati catchment in Gweru and had the lowest proportion of farmers who felt ZINWA's service was poor. ZINWA officials reported that the underlying factors against non-payment of water rates was that the farmers were still not self-sufficient and were not operating as commercial farmers but as communal subsistence farmers. One ZINWA official said; "We have fewer problems in servicing estates like Ratings and Macdom sugar estates that feed into the green fuel Ethanol plant at Chisumbanje in Chipinge, than smallholder irrigation schemes. Therefore, the solution for the low production levels and non-payment of rate lies in the commercialization of the schemes".

One ZINWA official from Manicaland Province revealed that Matanuska Banana company was sub-contracting farmers in Tanganda irrigation schemes to grow bananas under contract farming arrangements. It was working very well. It guaranteed farmers with a steady flow of income and the private company was also benefiting from the arrangement. With the land reforms and the fluidity of the land ownership structure in Zimbabwe, the former white commercial farmers in the farming industry survive better by partnering with the smallholder farmers under such arrangements like contract farming. ZINWA's experience with farmers under such partnership revealed that they were paying their water rates more consistently without any serious follow ups than those who were not under contract farming.

Results and discussion

All the irrigation schemes along the Save River were threatened by siltation which was preventing water from flowing on the surface between September and November every year. Farmers had to scoop the sand around the pump suction point to create a pool from which to access irrigation water. In Zimbabwe research has focused on the causes of siltation with Morton (2013) and Ncube (2013) highlighting how illegal mining by gold panners and Chinese mining companies in Matabeleland South were causing siltation of Insiza River and Umzingwane River. Siltation has reduced water holding capacity of Insiza, Inyankuni Lower Ncema Umzingwane and Upper by also most 40% due to rampant siltation (Morton, 2013; Ncube, 2013). In 5 out of the 8 irrigation schemes siltation was shown to be restricting the quantities of water available for irrigation and the scooping of sand was over burdening the already over-burdened farmers. The farmers' experience were similar to what farmers in Koraro village in Ethiopia have been experiencing since 2000, when the rivers' surface flow became seasonal due to both high siltation level and reduced rainfall, forcing farmers to scoop sand or digging holes in the dry riverbed (Ngigi, 2014). It can be deduced from the effects of siltation in the irrigation schemes that the future generation will not enjoy the same access to water as the current generation due to poor land use and mining practices with the catchment areas of the respective water source. In keeping with the concept of natural stock of capital that underpins sustainable development, sustainability of irrigation schemes can only be ascertained if the natural capital/stock, (water resource) remained intact, suggesting that their future will remain hopeless in the face of the unprecedented siltation. The WCED (1987) states that sustainable development happen when exploitation of resources, the direction of investments and institutional change are all in harmony and enhance the potential to meet the current and future human needs and aspiration. Farmers who participated in this study linked the siltation of water bodies to the economic hardships affecting the country as people began turning to gold panning in large numbers in the early 1990s when the country was hit by poor harvests due to droughts and high level of unemployment following the country's Economic Structural Adjustment Programme (ESAP) and its economic meltdown in the 10 years preceding 2009. The link between Zimbabwe' economic meltdown and siltation of rivers was consistent with the SLF understanding of the non-linearity nature of factors that affect livelihood strategies and the SLF assertion that sustainability was constrained by the environment of structures and processes (Davies, 1997). The 2010 report on climate change attributed the change in water discharge to low average rainfall and high evapotranspiration rate from the ever increasing high temperatures (IPCC, 2014). The problem of siltation in the irrigation schemes along Save River was exacerbated by the inequitable water uses between the upstream giant sugar plantation and the smallholder irrigation schemes in the downstream as the plantation would completely block river to create a big pool around their pumps at the expense of the smallholder farmers. ZINWA's failure to effect an equitable water sharing mechanism among the different farmers did not only compromise the sustainability of the irrigation schemes as it did not only affect the cropping cycles of the schemes but also the willingness of the farmers to contribute towards water bills which in turn was critical to sustainable of ZINWA as the organisation relied on what the farmers were paying to finance its operation. The concept of equity that underpins the concept of sustainable development was premised on the realisation that the unjust society or practices are unlikely to be sustainable in environment or economic terms in the long run (Agyeman et al., 2002). In trying to explain the poor state of irrigation farming in Sub Saharan Africa, Barker & Molle, (2004) indicated that there has been a serious lag in the development of appropriate institutions to deal with the equitable allocation of water among competing users and strategically integrate the management of different stakeholders to satisfy the different needs of smallholder farmers. The research study found out that in almost all irrigation schemes ZINWA could not respond to pump breakdowns, failed to avail sufficient quantities of irrigation water throughout the year yet it continued to levy farmers consistently even during the months when farmers had limited access to irrigation water and its officials were reportedly stealing from the irrigation schemes. Farmers also blamed ZINWA for failing to fix the gravity powered water extraction system that was vandalised by fish mongers at Mutorahuku dam and for failing to attend to the leaking Insukamini dam. The institution was also blamed for running a rigid service regime at the expense of the poor farmers. The concept of sustainable development calls for the identification and removal of such accumulated rigidities and impediments as well as the enhancement of the lost renewal capacities in institution to enhance sustainable development (Rigby & Caceres, 2001). The weak response to water breakdowns was contrary to the experiences of farmers in most Asian countries where, when a dam appeared to be leaking, the operating authority was usually under enormous pressure to repair the leak to save farmers from losses and the lives of the people in the downstream (Moore, 2011; International Atomic Energy Agency, 2014).

The fact that farmers were not happy with the service they were getting from ZINWA and yet were compelled to pay and, at times, short-changed, and also lacked the capacity to engage ZINWA and other related stakeholders such as Macdom to hold them accountable, mirrored the problems of insecure water rights which were reported in Philippines, Turkey, Mexico, Colombia and Argentina during the 1980s. The problems in these countries were attributed to farmers' lack of capacity and mechanisms for reliable legal and technical support services and for lobbying in governmental water policy forums (Moigne and Easter, 1992). It can be deduced from the above discussion that ZINWA failed to embrace the basic tenet of sustainable development, the concept of intra-generational equity (fairness in allocation of resources between competing interests), to enhance sustainability of both their business and that of the smallholder farmer (Agyeman et al., 2002). Contrary to the experiences in these schemes, it was revealed that Chile had an effective law enforcement mechanism that protected users from detrimental third party effects, part of which was an independent judiciary system that was monitoring water sharing among different users and reprimanding inefficient water authorities (Moigne and Easter, 1992). The current research discovered that the absence of this link between payment and performance possibly explains why 7 out of the 8 schemes had outstanding ZINWA bills. Although there was no known research in Zimbabwe on the link between performance of service provision and farmers' willingness to pay utility bill, a number of researches in Asia predicted a high defaulting rate on water bill where farmers lacked the incentive to pay due to lack of a sustainable link between payment and performance (Barker and Molle, 2004; World Bank, 2008; Kadigi at al., 2012). In Morocco, increased water charges have been accompanied by improved service, hence greater willingness to pay on the part of the farmers (Kadigi at al., 2012). It was also revealed that the farmers were not taking proactive measures in maintaining proper infield water management practices like maintaining infield canals in good working condition although the activity did not require any monetary commitments. Good stewardship of limited resources, ability to maintain wellness of infrastructure and ability to take responsibility and ownership enhances the sustainability potential of interventions (Grant, 2010). Poor production levels were also shown as the major threat to the sustainability of the smallholder irrigation schemes as there was a correlation between high levels production and demonstrated willingness to contribute towards electricity and water bills. This correlation attests to the inter-linkages of different systems connected to smallholder irrigation scheme as the production system affected the water supply system which in turn was affected by the input, output and financial markets as well as the effectiveness of the IMC and quality of institutional service delivery.

It was revealed that ZINWA was riding on the law to bill and to enforce payment by farmers, yet its engagement with farmers lacked materiality. The concept of social sustainability, inclusion and participation of multiple perspectives, hinted that for development initiatives and engagements to be sustainable, they need not be prescribed by law but that all players and agents must contribute to it and derive value from it (Phuhlisani Solutions, 2009; Rogers et al. 2013). The way the smallholder farmers across the 8 irrigation schemes were enduring the poor services from ZINWA confirms SLA's assertion that the main problems the poor farmers face is that the processes and structures which frame their livelihood strategies may constrain them unless the state adopts pro-poor policies (Carney 2012). The sustainable development concept, as a discourse of ethics advocated for sustainable ways of doing business by organisations and governments (Jabareen, 2012). Therefore, the failure by ZINWA to professionally deliver some value into their service to the farmers predicted unsustainability, not only of the smallholder irrigation schemes but also of their business with and cash-inflows from the farmers.

Researches in Latin America confirmed similar inefficiencies with parastatals for several decades, where the providers of water and electricity were so poor that their services were deteriorating by the day and the poor farmers suffered most (Ferrand et al, 2004). Unlike the case with Zimbabwe where the water and electricity service provision has remained in the hands of parastatals, the provision of these services in Latin America, were handed over to private companies following some dramatic reforms, resulting in improved water and electricity supply to the poor smallholder farmers (Ferrand et al, 2004). The sand abstraction water pumping systems that could have guaranteed continuous water pumping was not given priority by the development agencies that developed and rehabilitated irrigation schemes along the Save River. In the eyes the unprecedented siltation, the water supply systems of the smallholder irrigation schemes would not be resilient to the increasing siltation of the Save river. The fact that the irrigation schemes were affected by floods and reduced river discharge was also a strong indicator of the fact that climate change adaptation was not streamlined in the rehabilitation of the irrigation schemes (Downing et al., 1994; Brown, & Lall, 2006; Brown, 2012). The failure by Engineers to consult locals in the siting of the pump plinth affirms the sustainable development concept of eco-form which asserts that sustainability can only be achieved where planning was done at the local level involving the intended beneficiaries (Grant, 2010). It is only through high level of local community participation that intended beneficiaries share ideas and use their indigenous knowledge to sustain their own projects such as the community irrigation scheme (Carney, 2005; Ofosu, 2011; Nyong et al., 2013). Ostrom (1994), in her study of the community smallholder irrigation schemes in Asia concluded that where community members were actively involved and the traditional management system embraced, most of the schemes were free from threat of inundation and flooding.

Conclusion

Unprecedented siltation of water bodies compounded with inequitable water sharing and poor catchment management were conspiring to frustrate the sustainability of smallholder irrigation schemes yet interventions in the schemes were not prioritizing sand abstraction water pumping system. The Zimbabwe National Water Authority (ZINWA) as the water governing body proved to be inefficient and its engagement of farmers as its major client was very poor. Farmers could not understand why they were compelled to pay water bills to ZINWA as they could not find the link between the water charges and the quality of the service they were getting. A combination of farmers' low productivity levels, debilitating dependency syndrome, ZINWA's poor service culture and political interference in water governance was affecting farmers' ability and willingness to contribute towards water bills. There was poor in-field water management and some schemes were poorly designed as there was no consultation of the local people on the designing of the pumping systems. The majority of the schemes were incurring frequent pump breakdowns and farmers had no reserved funds for pump repair and replacement investment.

Recommendations

- Smallholder irrigation schemes need to invest in sand abstraction water pumping system to adapt to the unprecedented levels of siltation in Save river.
- The Government need to improve the service culture of the water governing bodies and each irrigation scheme should have a replacement investment fund to allow for continuity of operations in irrigation schemes without reliance on external aid.
- ZINWA should work hand in hand with the Environmental Management Agency to reduce river siltation by curbing gold panning along river catchments and stream-bank cultivation. It should also invest in ways of de-silting water bodies or sand abstraction methods of abstracting water.

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