Evaluation of Water Delivery Performance in Irrigation Systems Subjected to Reuse of Agricultural Drainage Water and Improving the Water Quality by Reuse Regulation

（農業排水の再利用を行う灌漑用水路系の配水実効評価と再利用制御による水質改善）

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Evaluation of Water Delivery Performance in Irrigation Systems Subjected to Reuse of Agricultural Drainage Water and Improving the Water Quality by Reuse Regulation

By

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Abstract

The main problem facing farmers in the Nile Delta is water shortage at the ends of irrigation networks and canals. These problems have worsened as water demands have increased. Egypt's Ministry of Water Resources and Irrigation (MWRI) is currently trying to avoid water deficits by returning agricultural drainage water to the irrigation canals. Kafr El-Sheikh Governorate, they constructed culverts that connected canal ends with the main drain (Bhr Nashrat) to provide supplemental agricultural drainage backflows (SADB) to irrigation canals. However, this return is not controlled, and the flows are based only on differences in the hydraulic head. In Egypt, the reuse of agricultural drainage water is a supplemental to fresh water supply. Government pumping stations (official) and farmers' small diesel pumps (unofficial) lift water up from drainage canals and direct it back into the irrigation canals to reuse for agriculture, thereby increasing the available water resources of Egypt by 12.6%. However, as water passes through the soil and drainage network, it picks up salts, agricultural chemicals, and other pollutants, leading to differences in the quality of drainage and irrigation water. Therefore, mixing the two water types deteriorates the overall quality. The common practice in Egypt is to mix drainage into fresh water up to the point where the salinity of the mixed water is about 1,000 mg L^{-1}. This thesis consisting of two main studies.

- Evaluating the effectiveness of SADB to counteract water shortage when the water supply from head regulators (WSHR) is insufficient. Moreover, the water delivery performance was analyzed in terms of adequacy, dependability and equity. Two water supply conditions were tested: (1) fresh water supply (WSHR) only and (2) fresh water supply plus backflow (WSHR

plus SADB). During the summer (May–September) of 2008, SADB significantly improved the adequacy to meet farmers' water requirements in some months. Adequacy and dependability, therefore, improved from "fair" to "good". During the following winter (October–April), SADB improved adequacy and equity only in March and April since water availability was generally sufficient under WSHR.

- Investigating the efficiency of using backflow to supplement the fresh water irrigation and its effect on water quality in Kafr El-Sheikh Governorate: the indicator of water supply ratio (*WSR*) was employed. Two water supply conditions were tested: (1) WSHR only and (2) WSHR plus SADB. During the summer of 2008, *WSR* was 0.93, and it improved up to 1.27 by adding the backflow. During the following winter, *WSR* was 1.50, and increased up to 1.82 by adding the backflow. Based on the monitoring of salinity of water during the study period at four locations – head, middle, tail, and drain – the salinity significantly increased toward the end of the canals. The effect of backflow on the salinity was calculated improved salinity values were obtained by regulating the backflow. During the summer, backflow significantly deteriorated water quality, but only part of this backflow was actually required, in June and July, to avoid the shortage, and not to exceed the requirements. During the following winter, fresh water availability was generally sufficient; however, backflow still occurred, leading to unnecessary deterioration of the water quality. If backflow is controlled according to the actual requirements, the water quality would be improved. Based on this analysis, an estimated improvement in water salinity of over 30% was realized in June and July, and by 100% in May, August, September, and all winter months.

The freshwater supply approach used in the area should be modified to improve the management of water distribution. Farmers’ behavior must also be improved, since farmers at the canal's head tend to withdraw more water than they need, leading to shortages at the canal's end. The canal systems were designed to provide the maximum water requirements of the water-consuming summer crops, but this has led to an excess freshwater supply in the winter. Further measures should be considered to improve the management of water distribution. SADB should be controlled by gates and pumps and used to supply water only when WSHR cannot provide enough water. The mixing ratio of SADB water might therefore be higher at the tail of the branch canals. However, if the water quality is sufficiently good, drainage backflow may have the potential to conserve fresh water flowing from the canal head regulators or to increase the area under cultivation.

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Abbreviations

The following symbols are used in this thesis:

A = area of flow
AHD = Aswan High Dam
a_i = area of sub-region i
A_I = total irrigated area
ARC = Agricultural Research Center, Egypt
bcm = billion cubic meters
CRWS Cumulative Relative Water Supply
CV_{AI} = coefficient of spatial variation of the ratio $Q_{Di,t} / Q_{Ri,t}$
CV_T = coefficient of temporal variation of the ratio $Q_{Di,t} / Q_{Ri,t}$
CWR = crop water requirement
Ea = application efficiency
ET_0 = reference evapotranspiration
FAO = Food and Agriculture Organization
Fed = Feddan (unit of measuring areas commonly used in Egypt = 4,200 m^2)
h_{en} = entrance loss
h_{ex} = exit loss
h_f = friction loss
H_L = head loss
i = sub-region
IIIMP = Integrated Irrigation Improvement and Management Project
IIP = Irrigation Improvement Project
IWR = irrigation water requirement
k = number of sub-regions of the system (for performance indicators)
Kc = crop coefficient
L = culvert length

MWRI = Ministry of Water Resources and Irrigation of Egypt

n = manning’s roughness coefficient (for HEC-RAS model)

NWRC = National Water Research Center

P_A = adequacy indicator

P_D = modified dependability indicator

P_E = modified equity indicator

Q = flow rate in the culvert

$Q_{Di,t}$ = amount of water delivered

$Q_{Ri,t}$ = amount of water required

R = hydraulic radius (for HEC-RAS model)

Reff = effective rainfall

RIS Relative Irrigation Supply

RWS Relative Water Supply

SADB = supplemental agricultural drainage backflow

t = a certain time

T = time period

WMRI = Water Management Research Institute

WSHR = water supply from head regulators

WSHR plus SADB = water supply from head regulators plus backflow

WSR = water supply ratio

WUA = water user association

Chapter 1

General introduction

1.1 Background

Egypt is an arid country with little rainfall, so water management is very important. Without a proper management, water will become a constraining factor. The rapid increase of population, and related industrial and agricultural activities have increased the demand for water to a level that reaches the limits of the available water supply. The water availability from the Nile River is not increasing and possibilities for additional water are very limited. Egypt must safeguard its water resources against the growing population by increasing the efficiency of the various uses with respect to quantity and quality. In spite of water scarcity, more than 12.5×10^9 m^3 yr^{-1} of Nile Delta drainage water is annually discharged into the Mediterranean Sea (Zhu et al. 1998). Efforts exerted so far in improvement of irrigation systems have not been enough to direct farmers towards applying water-saving measures and improved cropping patterns (Abul-Naga 2009). In recent study by Mohsen et al. (2013), who considered the improvement of irrigation systems in the Nile Delta the most important attempts in Egypt, is to implement more effective irrigation technologies. Egypt faces great challenges due to its limited water resources by enforcement policies to improve the performance of the existing delivery system and its development (Mohsen et al. 2013).

In arid countries, such as Egypt, rapidly increasing food demand and limited water resources are a matter of great concern. Agriculture accounts for approximately 85% of the total water consumption in Egypt (MWRI 2005a). Therefore, optimum utilization of the limited water resources, for example, by improving the irrigation system, is very important. MWRI (2005a) in Egypt recognized this fact early on, and initiated a number of development projects to mitigate water wastage. From 1977 to 1984, the Egypt Water Use Project was in effect; it aimed to improve agriculture and water-management programs (EWUP 1984). In 1993, the World Bank launched the Irrigation Improvement Project (IIP) in a total area of 105,000 ha. The main objectives of the IIP were to improve irrigation infrastructure, water-distribution systems, and on-farm irrigation management. In 2004, the World Bank and MWRI initiated the Integrated Irrigation Improvement and Management Project (IIIMP) to increase irrigation efficiency and agricultural productivity as well as improve drainage and groundwater management. The total target area under the IIIMP is 210,000 ha, and this area is located in lower, middle, and upper Egypt (World Bank 2003). The entire project area has been divided into different command areas.

Performance assessment is an essential component of effective irrigation management. The IIP attempted to correct inequitable water distribution and water supply shortage at tertiary canals. Technical tests indicated that the construction of lined canals and buried pipes considerably increases distribution and field application efficiencies (Bos 1980). In addition, the replacement of individual pumping units with a centrally operated pumping system, which is managed by the users themselves through water user associations, improves irrigation efficiency. The shift from individual to collective pumping has reduced operational costs by one-third (Elshorbagy 2000; FAO 2005; MWRI 2005a; Elkassar 2007).

Egypt has adopted a water policy that involves cost sharing by establishing water boards and promoting self-management at the tertiary canal level. Water users themselves perform operational and maintenance works, and this trend toward user-driven management is a major step forward in institutional reform. About 85–90% of the construction cost was spent at the farm (tertiary canal) level for the improvement of infrastructure, including equipment (pump sets and gates), whereas 10–15% was spent on the main canals (WMRI 2005). The entire construction cost is expected to be recovered from the beneficiaries.

(El-Ganzori et al. (2000); Abdel-Azim and Allam (2005); El-Agha et al. (2011)) have indicated a water supply shortage in the IIP areas of El-Wasat (31,500 ha) and El-Manaifa (19,740 ha) in the Kafr El-Sheikh Governorate of northern Egypt (Fig. 1). As to safe agricultural water from lose in the costal lakes and the Mediterranean Sea, all previous agricultural development strategies have stressed the importance of maximizing returns on water use (Abul-Naga 2009). Egypt's Ministry of Water Resources and Irrigation (MWRI) has proposed the use of available drainage water within the project areas where this study area is located to supplement the fresh water supply during periods of shortage. Reuse of drainage water may solve this contradiction of water shortage and disposal to the sea. The use of drainage water is an important source for supplementing water resources in areas where irrigation water is scarce like Egypt. Three types of reuse practice can be distinguished; natural, official and non-official reuse:

Natural reuse of drainage water occurs where rivers or canals act as a drain for aquifer systems. Natural reuse is largely non-controllable except by modifying the amount of recharge that occurs, i.e., reduction of deep percolation from irrigation (El-Gamal et al. 2005).

Official reuse occurs through pumping drainage water from drainage canals to the irrigation canals. In Egypt, the reuse of agricultural drainage water provides an integral supplement to the fresh water supply, thereby increasing the country's available water resources by 12.6%. MWRI is able to track water quality parameters at over 300 sites. This data shows that the salinity of the drainage water being reused has increased, from an average of 945 mg L^{-1} in 1984 to over 1,200 mg L^{-1} by 1997 (Van Achthoven et al. 2004). The degraded water quality threatens the expansion and even the continuation of the reuse of drainage water from the main drains (official reuse) in the Nile Delta. Many reuse mixing stations have been under increasing pressure of water quality deterioration. Indeed, since 1992, seven of the twenty three main reuse mixing stations have been entirely or periodically closed (Hussein and Hatem 2008). El-Salam (peace) Canal, having a mixture of such drainage water and the Nile water (1:1 ratio), crosses the Suez Canal eastward to the deserts of north Sinai (Othman et al. 2012).

Non-official reuse is practiced by individual farmers, who decide when and how much drainage water will be used for supplementing their irrigation water supply (El-Gamal et al. 2005). The practice of unofficial drainage reuse affects the quantity and direction of water flow through the system. Since farmers have no choice but using drainage water when their canals are empty, they do not have the option of mixing the drainage water with freshwater before reuse. Instead, they apply the drainage water directly to their fields. As the water moves directly from drain to field, it does not directly affect water quality in the canals. But it does pass through the soil and thus directly affects soil salinity (Barnes 2012a).

1.2 Problem description

The main problem facing farmers in the Nile Delta are water shortages at the ends of irrigation networks and canals. MWRI is currently trying to avoid water deficits by returning agricultural drainage water to the irrigation canals. For example, in the Kafr El-Sheikh Governorate, where the study area of interest is located, some canals have an oversupply in some months and deficits in others. Ministry officials started a project by constructing culverts connected canal ends with the main drain (Bhr Nashrat) to provide supplemental agricultural drainage backflows (SADB) channeled through these culverts. However, this return is not controlled, and flows are based only on differences in the hydraulic head. Backflow successfully boost the water supply from head regulators (WSHR). However, some months have sufficient fresh water supply, but still the backflow occurred and unnecessarily deteriorates the quality. The quality of drainage water is low compared to irrigation water. Therefore, mixing the two water types deteriorates the overall water quality.

IIP aims to reduce inequity of water availability from canal head to tail implying that if cost recovery after implementing IIP remains a challenge that then as essential element of the program has not been effective. For example, field data have shown that in summer, water for rice irrigation is provided on a rotation basis (4/6 rotation; 4 ‘on’ days and 6 ‘off’ days); however, even during the ‘off’ periods, irrigation is carried out at some locations, usually upstream of branch canal, whenever water is available (McDonald Partners Ltd. 1988; Oad and Azim 2002). If water supply is insufficient and unequally distributed, farmers irrigate more frequently than scheduled (as to cover future distribution in supply). Some farmers irrigate their fields twice as often as other farmers, and some fields receive more than 4 times of applied depth to other fields for the same rice variety (Depeweg and Bekheit 1997). This inequitable distribution of water prior to the beginning of the IIP may have led to concerns among individual farmers regarding their share of potential benefits (Wichelns 1999).

1.3 Study objectives

The main objectives of the first part of this study were to monitor and evaluate quantitatively the effectiveness of using SADB to supplement the WSHR, since farmers face water shortages and depend on backflow from the main drain, Bhr Nashrat. For project planning and management, water delivery systems are often evaluated in terms of the desire to best meet the water requirements of the system's users. The focus in this part was to check the efficiency of the SADB to augment the shortage in the WSHR. A change in management of the irrigation waters based on a consideration of the network's performance across scales and on water quality will be necessary (El-Agha et al. 2011).

The ability to access a resource is often a marker of privilege, this is not necessarily the case for drainage water reuse. The most privileged are those who have no need for this recycled water (Barnes 2012a). Therefore, the second part objectives of this thesis were to check the effect of using backflow on the water quality deterioration. The unutilized backflow was calculated, and the improved water quality were estimated based on utilized backflow only. Farmers face water shortages and depend partially on backflow from the main drain, Bhr Nashrat. In our study area, MWRI has proposed the use of available drainage water within the project areas to supplement the fresh water supply during periods of shortage (MWRI 2005a). However, backflow exceeds the amounts required to make up the shortages. Sensitive crops grown in the area suffer from the increased irrigation water salinity, however as explained by El-Ganzori et al. (2000) the concentrations of common metals and salts still do not cause problems for soils and plants. Future demands will lead to increasing water salinity of the mixed water. Therefore, this requires more strict measures and management of reusing the SADB. An environmental management plan is also needed that will ensure safe reuse of drainage water after operation of the appropriate mixing locations and ratios (El-Ganzori et al. 2000).

Evaluating the efficiency of using backflow to supplement the water provided by the fresh water supply and examining the improvement in water quality when only the utilized volume of backflow was channeled back into the canals, would help planning and management of irrigation delivery system in the area.

1.4 Study methodology

The first part of this thesis focused on examining the effect of SADB during periods of WSHR shortage**.** Thus**,** dependability and equity indicators were modified based on the main objective in this study by omitting the assessment of oversupply. Original dependability and equity indicators express temporal and spatial variability in the ratio of the amount of water delivered to the amount required, both water excess and shortage are considered as deteriorating factors for those indicators. However, the modified indicators consider any shortage as defects whereas any excess is not cosidered as a problem. The calculations for the study area are within two cases. Case (1): water supply for the study area will be considered as supply from head regulators only. Case (2): backflow from the drain will be considered as additional water supply. Based on this evaluation, some data were required from the field to calculate the indicators. These data are cropping pattern, water levels, gate openings, discharges, and dimensions and data of culverts connecting channels with the Bhr Nashart drain. These measurements were measured from the period May 2008 until May 2009 by the Water Management Research Institute (WMRI) of National Water Research Center (NWRC) (MWRI 2005a). Calculations of daily water supply in the head of branch canal depend on calibration of head regulator; the following data are required for calculation, water levels at upstream, downstream and gate opening of head regulator. Calculations of daily backflow from the drain depends on calibration of culverts connecting canal with main drain (DCM 2001; HEC-RAS 2008) which requires the following data, tail water levels, drain levels and culverts dimensions. Calculations of water demand are based on CROPWAT model (FAO 2005). A water supply indicator was used in the second part of this study to measure the water delivery performance at the study area. Unutilized backflow were used to calculate the improved salinity values and to check the effect regulating the backflow on improving the salinity. These salinity values were evaluated against the performance standards proposed in guidelines by the Food and Agriculture Organization (FAO): salinity of up to 450 mg L^{-1} in irrigation water will not cause any problems; 450–2,000 mg L^{-1} may cause slight to moderate problems; and over 2,000 mg L^{-1} will cause severe problems for use in irrigation (Ayers and Westcot 1994).

1.5 Overview of the research

The study consists of six chapters. The following are summary for the chapters:

Chapter 1: Presents background, problem description, objectives, methodology and overview of this study.

Chapter 2: Presents literature review of previous studies related to water supply shortage, performance indicators, Egypt water resources, history of agricultural drainage reuse in the Nile Delta, types of agricultural drainage irrigation reuse in Egypt, measures of salinity, CROPWAT and HEC RAS models.

Chapter 3: Describes the region of interest in this study and methodology used, how the data was collected, and how it was analyzed as well as arranged.

Chapter 4: Describes details of the quantitative analysis of reusing agricultural water to compensate for water supply deficiencies.

Chapter 5: Describes details of the improving water quality by regulating reuse of agricultural drainage water.

Chapter 6: Includes summary, conclusion and recommendations of this study.

Chapter 2

Literature review

This chapter provides the research work that carried out studies related to the objectives stated in the previous chapter. The following topics mention water supply shortage, performance indicators, water resources of Egypt, history of agricultural drainage reuse in the Nile Delta, types of agricultural drainage water reuse in Egypt, measures of salinity, CROPWAT and HEC RAS models.

2.1 Water supply shortage

Water is essential for life, but it is a limited resource that must be protected and allocated among competing uses and users. Water scarcity affects every continent and is faced by many societies. Many studies reported the water shortage problems occurring all over the world. For example, as explained by Martinez (1994), fresh water available for human consumption, for social, economic and cultural needs and for environmental requirements is rapidly becoming scarcer. We are currently on the threshold of a serious water shortage (Martinez 1994). There are finite amounts of water that must be shared in common between various sectors, regions, and their users (Abu-Zeid 1998). Water shortages and needs are increasing, and the competition for water among urban, industrial, and agricultural sectors, is growing more intensive (Hamdy et al. 2003). Countries are subjected to water scarcity conditions if the "population has suppressed the level that can be sustained comfortably by the available water" (Postel 1997). Countries are considered as water stress regions when per capita water use falls below 1,000 cubic meters (Postel 1997). The food production takes up to 70 percent of all fresh water withdrawals per year (Abu-Zeid 1998). The irrigation agriculture as the major user of water is recognized to be the main source for additional demand. System efficiency improvements might meet one half of water demands by year 2025 (Johansson et al. 2002). It would increase the water productivity, as the crop production per volume of water will rise (Kijne 2001).

Although there is enough fresh water on the planet for human activities, it is inequitably distributed and too much of it is wasted. For example in Egypt, a recent assessment at the main canal level showed that crops utilize only 47% of the annual irrigation water supply and the rest is lost through drainage systems including percolation (El-Agha et al. 2011). To reduce this wasting of water, farmers must be motivated not to demand more water than necessary (Vandersypen et al. 2006). Water management is a vital issue that should be handled carefully in sustainable way to save every drop of water from loses. The aim of water management is to develop, distribute and protect the available water resources. In countries such as Egypt where water is scarce, water distribution among many users is of paramount importance. Egypt is an arid country with rare rainfall, and depends mainly on water carried in the Nile River from upstream countries, but the resource is under increasing stress because of increasing competition for the water. Egypt, before building Aswan High Dam (AHD), allowed one crop per year in large areas, and now perennial irrigation allows on average two harvests all over the Nile Valley and Delta (Holmen 1991). The main problem facing farmers in the Nile Delta is an insufficient water supply at the ends of the irrigation networks, especially in summer. Some new projects were introduced to ensure equitable water distribution, i.e., IIP, those main objectives is to achieve equitable fresh water allocation among the water users along the canal system (Abdel-Azim and Allam 2005). However, in some areas in the end of the irrigation system, there water shortage still occurs. Therefore, the MWRI has proposed the use of available drainage water within the project areas to supplement the fresh water supply during periods of shortage.

The negative impacts on agriculture due to drainage water reuse have to be kept minimal (El-Ganzori et al. 2000). In the 1980s, the reuse of agricultural drainage water became a formal Egyptian policy (Hussein and Hatem 2008). In coming years, reuse of drainage water will be a key solution to meet increasing regional demands for water (Abdel-Azim and Allam 2005). To permit reuse of drainage water, it might be necessary to implement a comprehensive water monitoring program throughout the Nile Delta region, including water in canals, drainage systems, groundwater, and aquifers, to assess water quality and allow modification of the agricultural drainage reuse policy on the basis of the results (Abdel-Azim and Allam 2005). In the area of interest of this study, all crops grown in the area suffer from the increase of the irrigation water salinity, although they already did so under the reference conditions (El-Ganzori et al. 2000). A detailed study should be implemented to identify the sources of pollution to the areas and to define the appropriate pollution control measures (El-Ganzori et al. 2000).

2.2 Performance indicators

The objective of an irrigation system is to deliver water supplied to farmers equitably and timely. Irrigation performance indicators were introduced by many studies to describe behavior of irrigation systems. It can help managers to understand how irrigation systems operate under different water supplies. Many researchers have proposed indicators to measure performance of irrigation systems and used on a number of irrigation systems (Levine 1982; Molden and Gates 1990; Bos et al. 2005). Many case studies used these performance indicators to determine the water delivery performance (Christopher et al. 2007; Korkmaz et al. 2009; Mohsen et al. 2013). Bos et al. (2005) recommeds performance indicators for use in assessment of performance of irrigation systems to support planing and improving projects. Operation of such systems is generally based on personal experience, whereas more training and proper communication (e.g., technology transfer) would improve management of the resource (Christopher et al. 2007). Designing a high-quality irrigation service requires managers to account for the capacity of the physical system and operation of the system to deliver water when required by the irrigation schedule of crops and the system's design (Christopher et al. 2007).

Levine (1982) presented two type of indicators, Relative Water Supply (*RWS*) and Relative Irrigation Supply (*RIS*), both of which were used for evaluation of water use performance. Sakthivadivel et al. (1993) described a new methodology for assessing water delivery performance through the use of the concept of Cumulative Relative Water Supply (*CRWS*). The major advantage of *CRWS* compared to *RWS* is that it can be used to represent graphically the ratio of supply to demand meaningfully for the whole season, while *RWS* is only useful for evaluating this ratio for a specific time period. ROS (2013) emphasized the importance of the performance indicators to achieve a sufficient understanding of the agricultural systems. Molden and Gates (1990) described a number of performance measures, adequacy, efficiency, dependability, and equity of water delivery for use in evaluation and design of new or rehabilitated irrigation water delivery systems. Previous evaluations of irrigation water delivery systems have used the indicators (adequacy, efficiency, dependability, and equity) proposed by Molden and Gates (1990) to evaluate existing systems, to plan and design new systems, and to rehabilitate old systems. For project planning and management, water delivery systems are often evaluated in terms of the desire to best meet the water requirements of the system's users.

In this study, our main objective was to evaluate the effectiveness of using supplemental agricultural drainage backflows (SADB) to supplement the water provided by water supply from head regulators (WSHR). Thus, this study did not account for the effects of oversupply and did not assess the system's efficiency, because insufficient water supply is the most serious constraint, and a study of water delivery performance at the tertiary canal level found that the adequacy, dependability, and equity indicators were generally worse than the efficiency indicator in the Nile Delta (Unal et al. 2004). Of the indicators proposed by Molden and Gates (1990), this study focused on adequacy, but also used their dependability and equity indicators to assess the effectiveness of the use of SADB in the study area. Dependability and equity indicators were modified by omitting oversupply, because the goal of study was to examine the effect of SADB during periods of a WSHR shortage (i.e., when oversupply is not a problem). The study area of interest is located in the Kafr El-Sheikh Governorate, Egypt (Fig. 1).

2.3 Water resources of Egypt

Egypt has a negative water balance, this leads to the use of non-conventional water resources, which represent 21.3% more water than is available as fresh water. Approximate annual fresh water amounts to 59.6 billion cubic meters (bcm) and is derived from Nile river (56.8 bcm), rainfall along the Mediterranean coast (1.8 bcm), and the non-renewable Nubian Sandstone Aquifer (1 bcm) (MWRI 2005a). Egyptians use 72.3 bcm each year, where 12.7 bcm represents the negative water balance. These extra water arising from agricultural drainage reuse (7.5 bcm), municipal wastewater reuse (2.9 bcm), and renewable groundwater extraction (2.3 bcm) (MWRI 2005a). These approximate estimations for Egypt water resources come from integrated water resources management plan (MWRI 2005b). The accuracy of these estimates is a matter of debate among international water experts, however they provide at least a good indication of different water sources in Egypt.

Oases and wells are limited and cannot cover water needs in the whole country. Thus, other sources must be considered (FAO 2003). Egypt is an arid country with little rainfall rarely exceeding 200 mm yr^{-1} along the North Coast (Abu-Zeid 1995). Rainfall is usually occurring during autumn and winter time and almost no rainfall at summer or spring. The annual rainfall decreases quickly away from the coastal area and scattered showers can hardly be depended upon for agricultural production (Abu-Zeid 1995). In the southern

Upper Egypt, Sinai, and along the Red Sea coast events of measurable rainfall may be encountered once every three years, sometimes developing into very short, but destructive, flash floods (MWRI 2005b). Generally, rainfall in Egypt is unreliable source due to its spatial and temporal variability.

The main source of fresh water in Egypt is the Nile River which represents about 95% of the fresh water resources. The 1959 treaty with Sudan fixes Egypt's share from the Nile at 55.5 bcm (Abu-Zeid 1995). About 85% of this water is driven from the Ethiopian Plateau and the remaining part comes from the Equatorial Plateau (Abu-Zeid 1995). Before the construction of the AHD, the river used to rise to high levels greater than the demand during the flood season, and usually drought occurred during the period from November to June (Abu-Zeid 1995). However, recently, engineers within Egypt's MWRI who operate the AHD, a 3,830 m-long barrier of rock fill that sits astride the river shortly after it enters Egypt, can in effect turn the river on and off (Barnes 2012a). The AHD has saved safe Egypt from floods and drought.

Egypt has four main groundwater aquifers: the Nile Aquifer, the Nubian Sandstone Aquifer, the Moghra Aquifer between the West of the Nile Delta and the Qattara Depression, and Coastal Aquifers on the North-Western coast (MWRI 2005a). Fresh water source which accounts for 1 bcm yr^{-1} is coming from the Nubian Sandstone Aquifer. Groundwater in the Nile Aquifer system and renewable aquifers is considered as a non-conventional water resource as it is replenished from the Nile by seepage from canals distribution system. Renewable groundwater extraction represents 2.3 bcm yr^{-1} (MWRI 2005a).

Wastewater reuse is considered as an important non-conventional water source in Egypt. Wastewater is estimated at 4.9 bcm yr^{-1} (FAO 2003). Recycled water is a reliable source of water that must be taken into account in formulating a sustainable water policy (Kamizoulis et al. 2003). It is estimated that Egypt has 22 operational wastewater treatment plants, and about 150 plants under construction (FAO 2003). Since 1900, sewage water has been used to cultivate orchards in a sandy soil area at El-Gabal El-Asfar village, near Cairo (FAO 2003). According to the law, reuse of treated wastewater is not permitted for food and fiber crops (Kamizoulis et al. 2003). Wastewater reuse should be practiced for cultivation of non-food crops such as timber trees and green belts in the desert.

Our focus in this study is on reuse of agricultural drainage water, which represents 12.6% of Egypt's annual supply (7.5 bcm yr^{-1}). Egyptians use Nile water multiple times on its journey through the country towards the tail end of the system. The main drains discharge a total of approximately 12.5 bcm yr^{-1}, either directly into the Mediterranean Sea or into the coastal lakes of Mariut, Edku, Burullus, and Manzala (Zhu et al. 1998). Egyptians do not consider drainage water as waste, but as a resource in the face of water scarcity. However, its diversion back into irrigation system for reuse deteriorates the quality of the water in the canals.

2.4 History of agricultural drainage reuse in the Nile Delta

Projects for the reuse of drainage water date back to the 1870s, when authorities started to divert two million cubic meters a day from one of the main drains in the delta into a canal to boost irrigation supplies during the period of low water prior to the annual Nile flood (El-Guindy and Amer 1979). In the 1930s, the administration completed a pumping station on a main drain in the Eastern Delta; this station was designed to propel water along the drain to its outlet point in the coastal Manzala Lake. However, officials found that the water being lifted at the pumping station was of a reasonable quality; therefore, they decided to channel it back into one of the branches of the Nile (Amer and Ridder 1989). In 1964, after construction of the AHD, the introduction of perennial irrigation in the Nile Delta and Valley of Egypt led to increased water demand. In the 1970s, the MWRI developed a specific policy for drainage water reuse. The increasing pressure on the nation's water resources from agricultural expansion and intensification in the Nile Delta and Valley, as well as agricultural expansion through desert reclamation, led to mounting claims on irrigation supplies, leaving some farmers with no option but to use drainage water (Barnes 2012b). In the 1980s, the reuse of agricultural drainage water became a formal Egyptian policy (Hussein and Hatem 2008). MWRI officials recognized that drainage water offered a good, short-term solution for enhancing the country's water supply, so reuse of drainage water will be a key solution for meeting increasing regional demands for water in the next decades (Abdel-Azim and Allam 2005). Agricultural drainage water is a relatively inexpensive and costs less than a US penny per cubic meter. Other measures for developing new sources of water, such as desalinating seawater, for example, costs almost one US dollar per cubic meter (Zhu et al. 1998). By 1984, 2.9 bcm of drainage water was pumped back into the main canals and the Nile’s branches (Rosetta and Damietta) for reuse (Ismail 2011). Since then, the ministry has further expanded its network of pumping stations so that by 2011 the official reuse had reached 7.5 bcm (Ismail 2011).

2.5 Types of agricultural drainage water reuse in Egypt

MWRI has traditionally focused on recycling water from the main drains, which hold the most drainage water; this is called “main reuse”. Pumping stations lift water from these drains and channel it into the main canals or branches of the Nile. A major problem results from the deteriorating water quality in many drains, which are polluted from municipal and industrial sources. Mixing of this water with canal water in a number of cases has threatened other water users located in downstream of the mixing points. For this reason, a number of main drain reuse stations have been closed in the past. This also poses a substantial problem for the Egyptian company responsible for provision of drinking water, since the water treatment plants also draw water from the canals (Van Steenbergen and Abdel Dayem 2007). Bringing these pumping stations into operation again would require great efforts to reduce the pollution loads. Therefore, alternatives for this type of reuse have to be developed.

One solution to the reuse of drainage water from larger drains would be to shift the reuse to smaller, less polluted drains in the upper part of the system. This is called intermediate reuse which would pump drainage water to lower order irrigation canals, where it would not have harmful impacts on downstream domestic water intakes (MWRI 2005a). The branch drains are shallower; thus, this method of reuse does not require huge pumping stations and is therefore less costly and the infrastructure is less prone to malfunction. However, MWRI officials are concerned that “intermediate reuse” will adversely affect their “main reuse” program by reducing the quantity and quality of water flowing down the branch drains into the main drains.

The amount of drainage water farmers are recycling back into the irrigation system is difficult to gauge. When farmers do not have the option of mixing the drainage water with fresh water before reuse, they instead apply the drainage water directly to their fields. This water moves straight from the drain to field, so it does not directly affect water quality in the canals. However, it does pass through the soil and thus directly affects soil salinity. Farmers use the drainage water to irrigate only if their irrigation canals are empty. This is the practice of what MWRI call unofficial reuse; and is a strategy for survival (Barnes 2012a). The amount of drainage water each farmer uses is relatively small, but the aggregate impact is large. The ministry estimates unofficial reuse to be between 2 to 3 bcm a year (Ismail 2011).

Pumps are commonly seen in rural areas and have been ever since low cost diesel pumps manufactured in India became widely available in Egyptian markets in the 1970s.

Throughout much of Egypt, these pumps sit on the banks of canals, lifting water up to the fields for irrigation. In some cases, though, the channels on which these pumps operate are not canals but drains. To an outsider, the distinction is not always clear. Drains are deeper and often dirtier, but otherwise look quite like canals. Farmers, though, have no trouble telling the difference.

2.6 Measures of salinity

The average level of salinity in the main drains is 565 mg L^{-1}, but can reach up to 6,000 mg L^{-1} in northern parts of the delta near the coastal lakes (Brown et al. 2003). It is possible to irrigate with saline water and still maintain good levels of production using what is called biosaline agriculture, but this requires careful land management practices, which although piloted in Egypt (EL-Bably 2002; Barnes 2012a). With increasing distance downstream, water quality deteriorates in the river, canals and drains. The drains in the northern parts of the delta are wide and full of dark, polluted water with high salinity – on average, over 2,800 mg L^{-1} (Zhu et al. 1998). The Nile's large discharge quantities mean that salts and pollutants are highly diluted, leading to salt concentration levels below those found in the drains. Therefore, the Nile's salinity remains within the bounds of what is considered to be fresh water (typically under 500 mg L^{-1}), increasing from 110 mg L^{-1} at Aswan to just 280 mg L^{-1} at Cairo, 650 km to the north (Brown et al. 2003).

The quantity of water that can be lift from the drain depend on its quality. Less drainage water quality we have, less mixture quality we obtain. Therefore, the salts that the drainage water picks up along its journey determine its potential for reuse. What water becomes after drainage water reuse depends not only on the quality of the drainage water, but also on how much freshwater is mixed in with it (Barnes 2012a). Since salinity is a measure of the concentration of salts, the more fresh water is added, the less saline the mixture will be. Egypt drainage system consists of ditches, pipes, and channels that drain Egypt's agricultural lands. About 60% of the Egypt's cultivated land is served by a subsurface drainage system, comprising a network of pipes below the surface, which capture unused water from the soil. The rest of the land is covered by drainage ditches, which border each field. Drainage water from the surface and subsurface systems meets in the open branch drains, which channel water into the main drains (Barnes 2012a). Drainage is therefore a converse flow to irrigation. Whereas the irrigation network channels water from a single source (the river) to multiple points of outlet (the fields), the drainage network transfers water from multiple sources (the fields) to a single point of outlet (the drain). Both systems channel water, but the quality of water is different (Barnes 2012a). Pumps interrupt this cycle of drainage flow to the sea. Pumping stations operated by the ministry, lift drainage water back into the main canals, blending it with Nile water, to produce mixed water.

MWRI officials judge the drainage reuse policy based on good versus bad water; however, water quality is not an absolute concept, but has connotations of both scientific understanding and cultural beliefs (Alley 2002). From a national planning perspective, this salinity threshold is critical because it determines how much the government will be able to boost the country's water supply. Based on this threshold, records of water quality in each part of the canal network, and measurements of discharge in each canal section, it is possible to calculate how much water is available at or below that salinity for potential reuse (Barnes 2012a). In the mid-1990s, a team of international consultants, working with MWRI, conducted an evaluation of Egypt's maximum reuse potential. The team's target salinity level of 1,500 mg L^{-1} led to a reuse potential of 8.1 bcm. However, the ministry raised the target salinity level to 3,000 mg L^{-1}, so the team calculated a significantly higher reuse potential of 13.3 bcm, almost two times its current level. The team ultimately recommended that the ministry should adopt an intermediate threshold value of salinity of 2,250 mg L^{-1} for drainage water reuse. This would mean that Egypt could achieve a maximum reuse of 9.6 bcm, almost 30% higher than its current official reuse (Zhu et al. 1998).

2.7 CROPWAT and HEC RAS

CROPWAT is a decision support system developed by the Land and Water Development Division of the Food and Agricultural Organization (FAO) for planning and management of irrigation. CROPWAT is meant as a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements (*CWR*) and irrigation water requirements (*IWR*), and more specifically the design and management of irrigation schemes. To improve management practice, experimental data based the irrigation management model can be applied for estimating *CWR*. Crop coefficients (*Kc*) have been used to estimate evapotranspiration for specific crops by measuring potential or reference evapotranspiration. *Kc* must be derived empirically for each crop based on local climatic conditions (Doorenbos and Kassam 1986). Chen (1997) used Penman–Monteith method and meteorological data of Taipei, Hsinchu, and Kaohsiung from 1951 to 1990 to estimate the values of reference evapotranspiration (ET_0) in every 10 days for different recurrent periods in different areas of Taiwan. Cavero et al. (2000) applied CROPWAT model to simulate maize grain yield reduction caused by water stress under semiarid conditions. The irrigation management model of CROPWAT, designed by Smith (1992) of the FAO, was used in this investigation to assess the *CWR*.

HEC-RAS is a public domain code developed by the US Army Corp of Engineers (USAC 2002). It has been applied extensively in calculating the hydraulic characteristics of rivers (Carson 2006). It performs 1D steady and unsteady flow calculations on a network of natural or man-made open channels. Basic input data required by the model include the channel network connectivity, cross-section geometry, reach lengths, energy loss coefficients, stream junction information and hydraulic structures data. Cross-sections are required at representative locations throughout a stream reach and at locations where changes in discharge, slope, shape or roughness occur. Boundary conditions are necessary to define the starting water depth at the stream system endpoints, i.e., upstream and downstream. Water surface profile computations begin upstream for subcritical flow or downstream for supercritical flow. Discharge information is required at each cross-section in order to compute the water surface profile.

Chapter 3

Study area and methodology

In Egypt, the MWRI has a plan for reusing agricultural drainage backflow to boost water supply. The common practice in Egypt is to mix drainage water into irrigation water upto point when the salinity of the mixed water is about 1,000 mg L^{-1}. MWRI constructed culverts in the region of interest in this study of interest to channel the draiange water back into the canal to boost the water supply and make up the shortage. The quality of drainage water is lower than that of irrigation water. Thefore, there are two main interesting questions in this study: Firstly, does the backflow augment the shortage in water supply and sufficiently meet the crops requirements and achieve the goal from its use? Secondly, does the backflow deteriorates the water quality in the irrigation canal?

The first part of this study focused in examining the effect of SADB during periods of WSHR shortage**.** Thus**,** modified dependability and equity indicators were introduced by omitting the assessment of oversupply. Original dependability and equity indicators express temporal and spatial variability in the ratio of the amount of water delivered to the amount required, water excess and shortage, both of which are considered deteriorating factors for those original indicators. The modified indicators consider any shortage as defects whereas any excess is not cosidered as a problem, e.g. the amount of water delivered to the amount required ≤ 1.

The second part of the study investigated the efficiency of using backflow to supplement the fresh water irrigation and its effect on water quality in the region of interest in this study, Kafr El-Sheikh Governorate. The indicator of water supply ratio (*WSR*) was employed. Two water supply conditions were tested: (1) WSHR only and (2) WSHR plus SADB. Based on the monitoring of salinity of water during the study period at four locations – head, middle, tail, and drain. The effect of backflow on the salinity was calculated and improved salinity values was obtained by regulating the backflow.

This chapter provides the detailed information about region of interest in this study, data collected and methodology used to conduct this study. The following topics mentioned study area, water supply, water requirements, performance indicators, water supply ratio, unutilized backflow and improved salinity values, and finally the salinity.

3.1 Study area

The region of interest in this study is within the Kafr El-Sheikh Governorate in northern Egypt (Fig. 1), located in the western part of the Nile River Delta (31.21 °N 30.78 °E, 31.27 °N 30.85 °E), at a mean elevation of 20.0 m above sea level. One area located in the downstream regions of the study area is a part of the Nile Delta with saline groundwater; the salinity of the drainage water is 2,688 mg L^{-1}, so there is limited opportunity to reuse this water and it is channeled into Burullus Lake through open drains (DRI 2007). The study area has a Mediterranean-type climate with hot, dry summers and cool, wet winters. The maximum monthly average temperature is about 33.3 °C in July, the minimum is about 6.6 °C in January, and the mean annual temperature is 20.2 °C. Reference evapotranspiration (ET_0) is relatively high during summer, at 6.15 mm d^{-1} in June, and is a minimum at 2.17 mm d^{-1} in December (Table 3). The maximum relative humidity is 74% in November and the minimum is 53% in May. Mean wind speeds range from 1.0 m s^{-1} in October to 1.7 m s^{-1} in March. The soil originated from Holocene alluvial deposits, mainly dark greyish-brown sediments from the suspended materials in the Nile River (Eid et al. 2001). The average annual rainfall is low at about 63 mm yr^{-1}, occurring for twelve days a year, mostly as occasional thunderstorms, mainly in winter, from November to March. The main source of irrigation water is from the tail of the main canal, Meet Yazeed. Three branch canals (Saafan, Eliwa, and El-Masharka) branch from Meet Yazeed. These canals suffer from inadequate fresh water supply from head regulators. Therefore, drainage water from the main drain (Bhr Nashrat) is used to supply the study area during shortage. For this study, salinity measurements during the study period were obtained from the Water Management Research Institute (WMRI) of the National Water Research Center (NWRC). These measurements were taken once every month at four locations: head, middle, tail, and drain. The quality deteriorated from 400 mg L^{-1} at the head and reached a value little less than 1,000 mg L^{-1} at the drain. Canal water quality deterioration by backflow was within the acceptable level.

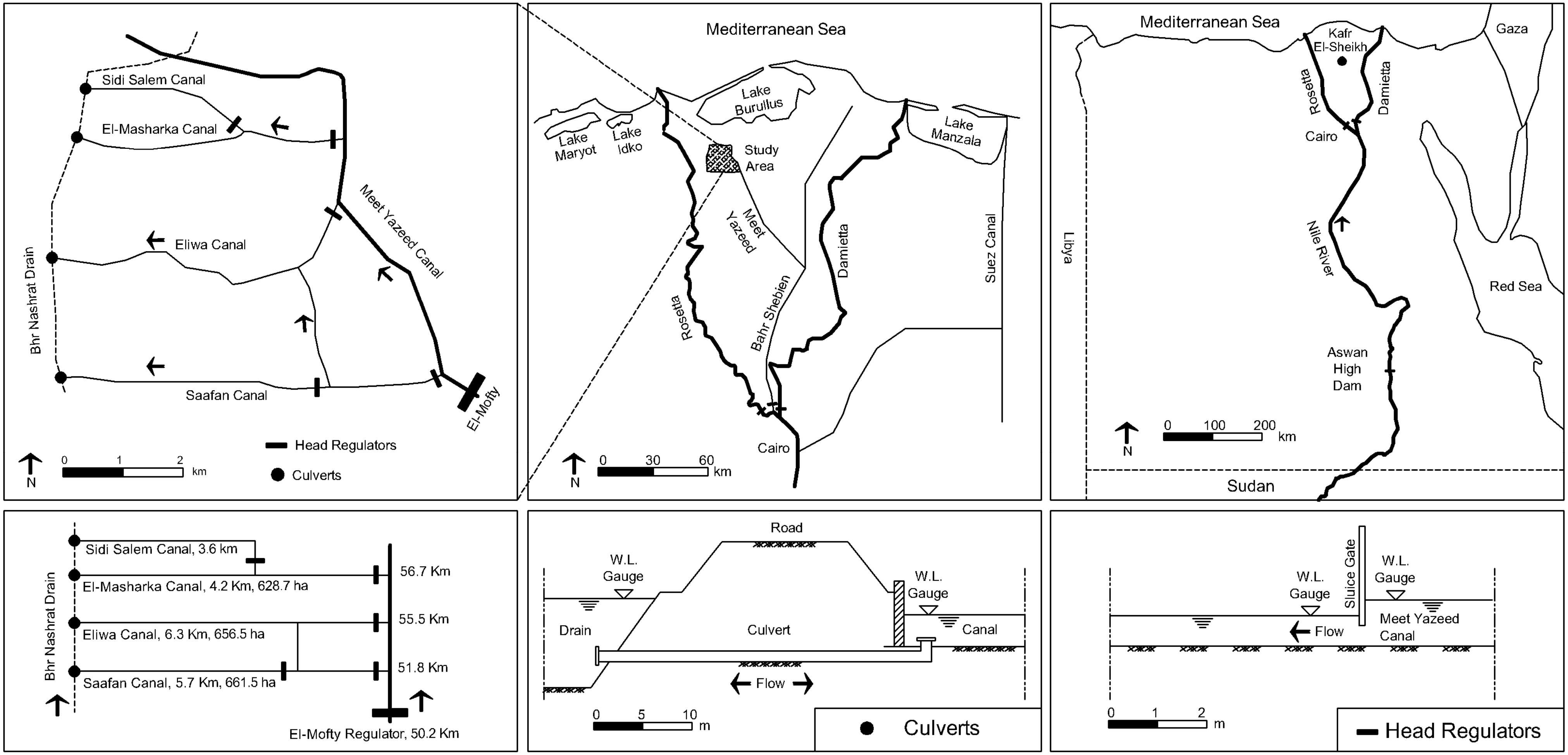


Figure 1. The region of interest in this study.

3.2 Water supply

As mentioned earlier, the study area suffers from inadequate fresh water supply owing to its position at the tail of the Meet Yazeed feeder canal. Managers have proposed compensating for shortages by using the water from the Bhr Nashrat drain. The potential water supply for the study area thus comprises a fresh water supply and agricultural drainage backflow. Continuous discharge records are not collected, and fresh water supply data are collected only four times per month. However, gate openings and water levels at the upstream and downstream of the head regulators were continuously monitored with automatic recorders (OTT Thalimedes, Hydromet-Germany) during the study period by staff of the WMRI of the NWRC, so it was possible to establish a relationship between water levels in the canals, gate openings, and discharges. Flow heights were converted into discharges using individual rating curves for each canal (Table 1, Fig. 2). These curves were verified at each measurement point by using the flow velocities and the cross-sectional areas of the canals. The curves were then used to obtain the discharges, which were summed to give the monthly fresh water supply.

No discharge records were available for backflow of agricultural drainage at the culverts connecting the canals with the main drain, and there are no control gates nor valves. However, culvert diameter and length were measured and water levels were continuously monitored at the canal tail and the main drain with automatic recorders during the study period. Daily discharges were calculated using HEC-RAS program. HEC-RAS model requires details of cross sections of the canal and upstream flow rate for execution. Use of the energy conservation equation allows calculation of the velocity and water depth of the given cross section. HEC-RAS computes energy losses caused by structures such as culverts, in three parts. The first part consists of losses that occur in the reach immediately upstream from the culvert, where the flow contracts towards the opening of the culvert. The second part consists of losses that occur as flow travels into, through, and out of the culvert. The last part consists of losses that occur in the reach immediately downstream from the culvert, where an expansion of flow takes place. Culverts which connect canal ends with the main drain (Bhr Nashrat) for the three studied canals were modeled with HEC-RAS for each day during the study period to calculate the discharge passing through the culverts. If the water level at the canal tail was higher than that at the main drain, water flowed into the main drain. When the water level in the main drain exceeded that in the canal tail, backflow occurred. Data required for each simulation were culvert length, material, diameter, entrance and exit loss coefficients, river cross sections, Manning's roughness coefficient, downstream water level, and discharge. The culvert used in the study area is circular in cross section, with a 0.8 m diameter and 30 m length (Table 2). For each simulation, discharge was estimated, actual downstream water level was used in the simulation, and the corresponding upstream water level was calculated from HEC-RAS model and then compared to the actual upstream water level. Discharge was repetitively assumed until sufficient agreement between the actual and calculated upstream water level was obtained. Various coefficients were given based on the HEC-RAS model (HEC-RAS 2008). The head loss, H_L is computed using the following formula:

$$H_L = h_{en} + h_f + h_{ex} \qquad (1)$$

where: h_{en} = entrance loss (m)

h_f = friction loss (m)

h_{ex} = exit loss (m)

The friction loss in the culvert is computed using Manning's formula, which is expressed as follows:

$$h_f = L\left(\frac{Q\,n}{A\,R^{2/3}}\right)^2 \qquad (2)$$

where: h_f = friction loss (m)

L = culvert length (m)

Q = flow rate in the culvert ($m^3\ s^{-1}$)

n = Manning's roughness coefficient

A = area of flow (m^2)

R = hydraulic radius (m)

The exit energy loss is computed as a coefficient times the change in velocity head from just inside the culvert, at the downstream end, to outside of the culvert at the downstream end (HEC-RAS 2008). The entrance loss is computed as a coefficient times the absolute velocity head of the flow inside the culvert at the upstream end (HEC-RAS 2008).

The daily discharges were summed to obtain the monthly agricultural drainage backflow for each canal.

Table 1. Equations for discharge from the head regulators.

Canal	Season	Flow status	Equation	r^2
Saafan	summer	submerged	$y = 0.91\ GO + 0.449$	0.72*
	winter	submerged	$y = 2.2143\ GO - 0.441$	0.79*
Eliwa	summer	submerged	$y = 3.1676\ GO + 0.1074$	0.73*
	winter	submerged	$y = 1.4768\ GO + 0.3322$	0.83*
El-Masharka	summer	free flow	$y = 0.0863e^{1.521} \times GO$	0.76*
	winter	free flow	$y = 0.0228e^{2.3607} \times GO$	0.78*

$y = Q\ \Delta h^{-1}$, where Q = discharge (m^3/s), Δh = difference in the hydraulic head (m), e = 2.72, GO = gate opening (m), and r^2 = coefficient of determination (*: significant at $P < 0.05$).

Table 2. Dimensions and parameters of culverts that modeled with HEC-RAS

	Diameter (m)	Length (m)	Cross section	Material type	Manning's roughness coefficient	Entrance loss coefficient	Exit loss coefficient
Saafan	0.80	30	Circular	Concrete	0.017	0.5	1.0
Eliwa	0.80	32	Circular	Concrete	0.017	0.5	1.0
El-Masharka	0.80	27	Circular	Concrete	0.017	0.5	1.0

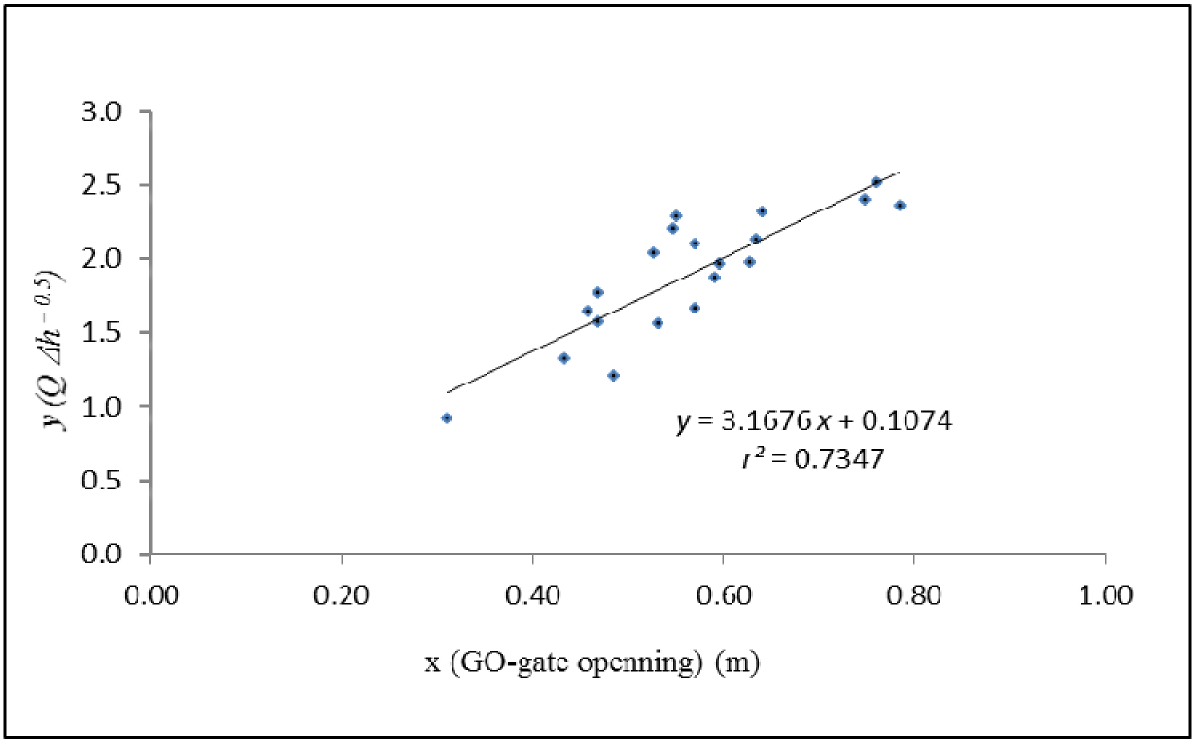


Figure 2. An example of discharge calibration for summer irrigation in the Eliwa canal. Explanation of the parameters and the equations for the other canals and seasons are shown in Table 1.

3.3 Water requirements

Data on cropping patterns in the study area were collected from the agricultural directorate of each canal's command area. Rice, cotton, maize, and a variety of summer vegetables were grown during the summer. Wheat, alfalfa, sugar beet, and a variety of winter vegetables were the main winter crops (Fig. 3 and Table 5). Calculation of water demand was based on the CROPWAT model (FAO 1992). Water application efficiency (by surface irrigation) was assumed to be 80%, and conveyance efficiency to be 70% (NWRC 2003). CROPWAT for Windows v.4.3 is a software for irrigation planning and management, developed by several scientists (Smith et al. 1991; Smith 1992; Smith 1993). This model can be considered as a useful tool to support decision making to calculate the reference crop evapotranspiration (ET_0) and crop water requirements (*CWR*). CROPWAT model requires climatic, crop, and soil data as inputs for the model: *CWR* as shown in Table 3 was calculated as:

$$CWR = ETo \times Kc \qquad (3)$$

where ET_0 is reference crop evapotranspiration, which represents the potential evapotranspiration of a well-watered grass crop. *Kc* is crop coefficient. The *Kc* is attributed by crop type, stage of growth and plant health. Values were calculated using the FAO Penman-Monteith equation based on geographic and geologic information of latitude, longitude, and altitude, and monthly climatic average data of the minimum and maximum air temperature (°C), relative humidity (%), sunshine duration (h), and wind speed (m s^{-1}); Climatic data were obtained from records at the Sakha Station of the Agricultural Research Center (ARC), Egypt.

A cropping pattern consisting of the crops and their planting date, crop coefficient data files (including *Kc* values, stage days, root depth, depletion fraction), and the area planted (0-100% of the total area); a set of typical crop coefficient data files are provided in the program. Planting dates were obtained from the agricultural cooperatives in the canal's command area. *IWR* was then calculated for the entire study period (Table 5).

$$IWR = (CWR - R_{eff}) / Ea \qquad (4)$$

Where R_{eff} = effective rainfall, and Ea = application efficiency 80% (NWRC 2003)

The theoretical *IWR* in the areas around the monitored canals was calculated for comparison with the water supply (Fig. 4).

Table 3. Reference crop evapotranspiration (ET_0), rainfall, and Crop water requirements (*CWR*) during the summer of 2008 and the winter of 2008–2009.

	ET_0 (mm d^{-1})	Rainfall (mm d^{-1})	Crop water requirements (*CWR*)							
			Summer (mm d^{-1})				Winter (mm d^{-1})			
			Cotton	Rice	Maize	Other	Alfalfa	Wheat	Sugar beet	Other
May 2008	5.53	–	4.4	4.2	1.3	3.0	–	–	–	–
June 2008	6.03	–	5.3	7.7	2.8	4.2	–	–	–	–
July 2008	6.15	–	5.1	7.0	4.7	5.0	–	–	–	–
Aug. 2008	5.75	–	4.6	6.1	4.4	5.1	–	–	–	–
Sept. 2008	5.01	–	3.3	2.7	–	4.5	–	–	–	–
Oct. 2008	3.77	–	–	–	–	–	1.2	–	0.7	1.6
Nov. 2008	2.83	–	–	–	–	–	1.8	1.0	0.9	1.6
Dec. 2008	2.17	–	–	–	–	–	1.0	0.5	0.8	1.0
Jan. 2009	2.28	0.5	–	–	–	–	1.7	1.5	1.8	1.6
Feb. 2009	2.76	0.9	–	–	–	–	2.4	2.6	2.8	–
Mar. 2009	3.64	0.3	–	–	–	–	2.6	3.0	3.0	–
Apr. 2009	4.76	0.4	–	–	–	–	3.4	2.8	1.7	–

3.4 Performance indicators

In its path from the AHD to irrigated fields in our study area, water is diverted from its natural course, then conveyed and distributed through water-delivery networks to farms within the irrigation system. The success of an irrigation water delivery system can be measured by how well it meets the objectives of delivering an adequate and dependable supply of water in an equitable, efficient manner to the users. If an adequate and timely amount of water does not arrive at the farms, crop yields may suffer and net returns from farm may be reduced. When evaluating how well the system is functioning and when making decisions about the design or rehabilitation of a system, it's necessary to define objective measures of system performance and prescribe standards for assessing the values of those measures (Korkmaz et al. 2009). Performance measures should be functions of state variables that have a direct impact on fulfillment of the system's objectives, should be intuitively easy to interpret, and should be relatively easy to measure or predict (Molden and Gates 1990). Once performance measures have been estimated for a given state of the system, their values must be assessed according to the performance standards. Water supplied to the canals must be measured, and a system to monitor and evaluate water delivery must be implemented. Water users should also be educated about efficient water use (Korkmaz et al. 2009).

The rest of this section presents the indicators used to describe the irrigation system's performance. The values of these indicators were calculated during each growing season (summer and winter), both for a system based only on WSHR and for a system based on

WSHR plus SADB. The indicators were evaluated against the performance standards proposed by Molden and Gates (1990), which are summarized in Table 4.

Adequacy: delivery of the required amount

Adequacy (P_A) is defined as the ability of an irrigation system to provide the required amount of irrigation water, without consideration of whether excess water is provided. This study used the original adequacy indicator proposed by (Molden and Gates 1990):

$$P_A = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{1}{A_I}\sum_{i=1}^{k} a_i \frac{Q_{Di,t}}{Q_{Ri,t}}\right) \qquad (5)$$

$$\sum_{i=1}^{k} a_i = A_I$$

where $Q_{Di,t}$ is the amount of water delivered, and $Q_{Ri,t}$ is the amount of water required in sub-region i with area a_i during a certain time (t), k is the number of sub-regions in the irrigation system, and A_I is the total irrigated area. When $Q_{Di,t} \geq Q_{Ri,t}$, the amount delivered was considered to be adequate, without consideration of the excess; that is, the ratio $Q_{Di,t}/Q_{Ri,t}$ was set at 1.00. P_A value close to 1.00 indicated adequate water delivery, whereas a value of <0.80 indicated inadequate water delivery.

Modified dependability: uniform delivery over time

The original dependability indicator proposed by Molden and Gates (1990) expresses the temporal variability in the ratio of the amount of water delivered to the amount required in a region, it uses the value of $Q_{Di,t}/Q_{Ri,t}$, regardless its more or less than 1. The modified dependability indicator based on shortage that was used in this study (P_D) expresses the canal's ability to provide water at the desired time without consideration of the excess (i.e., It did not account for the effect of values >1). In contrast, the modified dependability indicator based on excess expresses the canal's ability to provide water at the desired time without consideration of the shortage (i.e., it did not account for the effect of values < 1). They can be expressed as:

$$P_D = \frac{1}{A_I} \sum_{i=1}^{k} a_i . \mathrm{CV_T} \left(\frac{Q_{Di,t}}{Q_{Ri,t}} \right) \qquad (6)$$

$$\sum_{i=1}^{k} a_i = A_I \quad t = 1 \sim T$$

where CV_T ($Q_{Di,t} / Q_{Ri,t}$) is the coefficient of temporal variation of the ratio $Q_{Di,t} / Q_{Ri,t}$ during time period T. For dependability based on shortage and when $Q_{Di,t} \geq Q_{Ri,t}$, the amount delivered was considered to be adequate, without consideration of the excess; that is, the ratio $Q_{Di,t} / Q_{Ri,t}$ was set at 1.00. For dependability based on excess and when $Q_{Di,t} < Q_{Ri,t}$, the amount delivered was considered to be efficient, without consideration of the shortage; that is, the ratio $Q_{Di,t} / Q_{Ri,t}$ was set at 1.00. P_D values equal to or close to 0 indicate that water delivery was relatively uniform and thus dependable.

Modified equity: delivery of a fair amount

The original equity indicator proposed by Molden and Gates (1990) expresses the spatial uniformity of the ratio of the amount of water delivered to the amount required during a given time period; in some cases, $Q_{Di,t} / Q_{Ri,t} > 1$. The modified equity indicator based on shortage expresses the degree of variability in relative water delivery from point to point throughout the irrigated area without consideration of the excess. In some cases, $Q_{Di,t} / Q_{Ri,t}$

< 1. On the other hand, the modified equity indicator based on excess (P_E) expresses the degree of variability in relative water delivery from point to point throughout the irrigated area without consideration of the shortage. They can be expressed as:

$$P_E = \frac{1}{T}\sum_{t=1}^{T} \mathrm{CV}_{\mathrm{A_I}}\left(\frac{Q_{Di,t}}{Q_{Ri,t}}\right) \qquad (7)$$

where CV_{AI} ($Q_{Di,t}$ / $Q_{Ri,t}$) is the coefficient of spatial variation of the ratio $Q_{Di,t}$ / $Q_{Ri,t}$ in area A_I. For equity based on shortage, the amount delivered was considered to be adequate when $Q_{Di,t} \geq Q_{Ri,t}$, without consideration of the excess; that is, the ratio $Q_{Di,t}/Q_{Ri,t}$ was set at 1.00. For equity based on excess the amount delivered was considered to be efficient when $Q_{Di,t} < Q_{Ri,t}$, without consideration of the shortage; that is, the ratio $Q_{Di,t}/Q_{Ri,t}$ was set at 1.00. Equity in water delivery was considered to be high if P_E was equal to or near zero.

Table 4. Performance standards used to evaluate the irrigation system (Molden and Gates 1990).

	Good	Fair	Poor
Adequacy	0.90–1.00	0.80–0.89	<0.80
Dependability	0.00–0.10	0.11–0.25	>0.25
Equity	0.00–0.10	0.11–0.25	>0.25

3.5 Water supply ratio (*WSR*)

A water supply indicator was used to measure the water delivery performance at the study area. The indicator of water supply rate (*WSR*) was calculated by the following equation (Levine 1982; Small and Svendsen 1990; Sakthivadivel et al. 1993; Korkmaz et al. 2009) :

$$WSR = \frac{Q_D}{Q_R} \qquad (8)$$

where Q_D is the amount of water delivered (m^3), and Q_R is the total irrigation water requirements for the area served (m^3). A value of $WSR = 1$ shows that enough water is being supplied to meet requirement, $WSR < 1$ that supply is less than requirement, and $WSR > 1$ that more water is being supplied than is required.

3.6 Unutilized backflow and improved salinity values

Relative unutilized backflow were used to calculate the improved salinity values and to check the effect of regulating the backflow on improving the salinity. Relative unutilized backflow $(Unutilizedbackflow(\%))$ was calculated by the following equation.

$$Unutilizedbackflow(\%) = \frac{fws + Backflow - Q_R}{Backflow} \times 100 \qquad (9)$$

Where fws is the fresh water supply (m^3), Q_R is the total irrigation water requirements for the area served (m^3). A value of $Unutilizedbackflow(\%)$ = 100% shows that all the backflow was not used effectively, $Unutilizedbackflow(\%) <$ 100% that only part of backflow was utilized effectively.

When 100% of the backflow were unutilized, the improved salinity values along the canal were considered is equal to the first salinity value measured at the entrance of the canal. When no backflow occurred, the improved salinity values were considered exactly the same as the actual measurements collected from the field. When part of the backflow were utilized, improved salinity values were calculated based on the utilized backflow $Utilized backflow(\%) = 100 - Unutilized backflow(\%)$ using the following equation.

Improved salinity = actual salinity × utilized backflow (%) (10)

The accuracy of these estimates is a matter of debate among international water experts, but they provide at least some indication of the improved salinity values.

3.7 Salinity

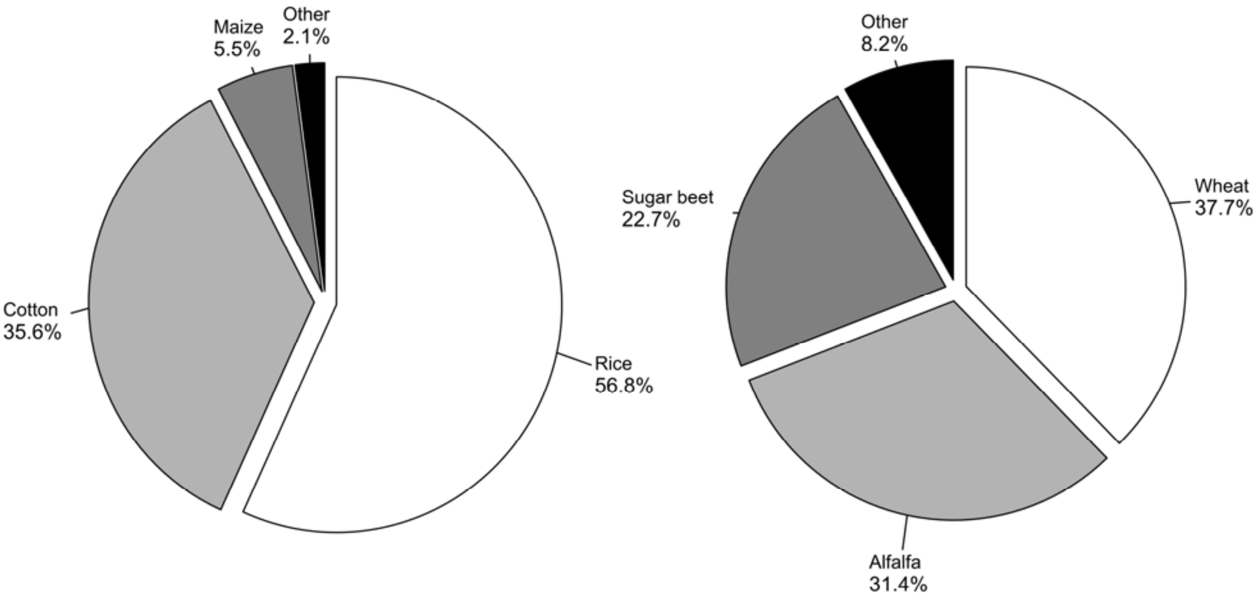
Salinity is a measure of the concentration of salts in water. Excessive salinity adversely affects crop production and yields especially for a number of crops such as most vegetables, maize, alfalfa, flax, and a number of fruit trees (MWRI 2005a). Thus, Egypt must reuse agricultural drainage more sensitively and accurately. Salinity measurement data were obtained during the study period from the WMRI of the NWRC. As mentioned before, these measurements were made once a month at four locations (head, middle, tail, and drain). These values were evaluated against the performance standards proposed in guidelines by the FAO: salinity of up to 450 mg L^{-1} in irrigation water will not cause any problems; 450–2,000 mg L^{-1} may cause slight to moderate problems; and over 2,000 mg L^{-1} will cause severe problems for use in irrigation (Ayers and Westcot 1994).

Chapter 4

Quantitative analysis of reusing agricultural water to compensate for water supply deficiencies

4.1 Crop pattern

The cultivation pattern did not differ greatly among the three branch canals. Rice and cotton were the main crops cultivated during the summer, accounting for 56.8% and 35.6%, respectively, of the total area (Fig. 3). Rice exceeded the government's stipulated maximum of 50%, which was implemented as a water conservation measure due to high water consumption by paddy rice (WAGS 2008). The high profit from rice cultivation compared with other summer crops encourages the farmers to ignore this regulation, and this situation calls for stricter monitoring of cropping pattern and more effective crop management policies (Arafat et al. 2010). During the winter, wheat and alfalfa were the main crops, accounting for 37.7% and 31.4%, respectively, of the total area. The seasonal *CWR* per hectare for the monitored branch canals totaled 10,394 $m^3\ ha^{-1}$ for rice, 8,511 $m^3\ ha^{-1}$ for cotton, and 4,930 $m^3\ ha^{-1}$ for maize during the summer, versus 4,482 $m^3\ ha^{-1}$ for alfalfa, 3,522 $m^3\ ha^{-1}$ for wheat, and 3,576 $m^3\ ha^{-1}$ for sugar beet during the winter (Table 5). Water consumption by other crops was much smaller than that by the three main crops during the winter, but was larger than that by the crop with the third-largest area (maize) during the summer.



Summer 2008

Winter 2008-2009

Figure 3. Cultivation pattern during the summer of 2008 and the winter of 2008–2009.

Table 5. Crop water requirements *(CWR)* during the summer of 2008 and the winter of 2008–2009.

	Crop water requirements (*CWR*) ($m^3\ ha^{-1}\ month^{-1}$)							
	Summer				Winter			
	Cotton	Rice	Maize	Other	Alfalfa	Wheat	Sugar beet	Other
May 2008	1,636	1,575	478	1,110	–	–	–	–
June 2008	1,999	2,884	1,039	1,577	–	–	–	–
July 2008	1,914	2,624	1,765	1,890	–	–	–	–
Aug. 2008	1,714	2,290	1,648	1,928	–	–	–	–
Sept. 2008	1,248	1,021	–	1,690	–	–	–	–
Oct. 2008	–	–	–	–	464	–	252	591
Nov. 2008	–	–	–	–	663	387	344	598
Dec. 2008	–	–	–	–	370	204	294	365
Jan. 2009	–	–	–	–	441	379	498	416
Feb. 2009	–	–	–	–	561	633	683	–
Mar. 2009	–	–	–	–	866	1,017	1,011	–
Apr. 2009	–	–	–	–	1,117	902	494	–
Total	8,511	10,394	4,930	8,195	4,482	3,522	3,576	1,970

4.2 Water supply and water requirements

Figure 4 shows the relationship between WSHR, WSHR plus SADB, and irrigation water requirements for the three branch canals during the summer of 2008 and the following winter. This figure permits two important comparisons: (1) WSHR versus the irrigation water requirements, and (2) WSHR plus SADB versus the irrigation water requirements. Water supply was generally higher in summer than in winter, as water requirements for summer crops were more than that for winter crops. However, mismatching occurred: shortage in summer, and oversupply in winter. Total WSHR released by irrigation district during summer were less than *IWR*. In contrast, total WSHR during the winter were more than *IWR*. *IWR* were intense in June and July in summer; March and April in winter. However, WSHR showed ineffective water distribution based on the requirements. Culverts are conveying water continuously, regardless of the excess that occurred during the winter. During the summer, water shortages occurred in June and July when only WSHR was used, because of ineffective water delivery, which indicates the need for SADB during these months. During May, August, and September, WSHR met the *IWR*, so there is no need to reuse the drainage water. The additional water provided by SADB was more than sufficient to compensate for the shortage of fresh water from WSHR. During the winter, WSHR was insufficient during March in the Eliwa canal and during March and April in the El-Masharka canal because of their location at the end of the irrigation network. SADB was required at these times to compensate for the shortage of water from WSHR. Water from SADB was more than sufficient to compensate for the water shortage during these months. Water from WSHR was sufficient for the Saafan canal in all months.

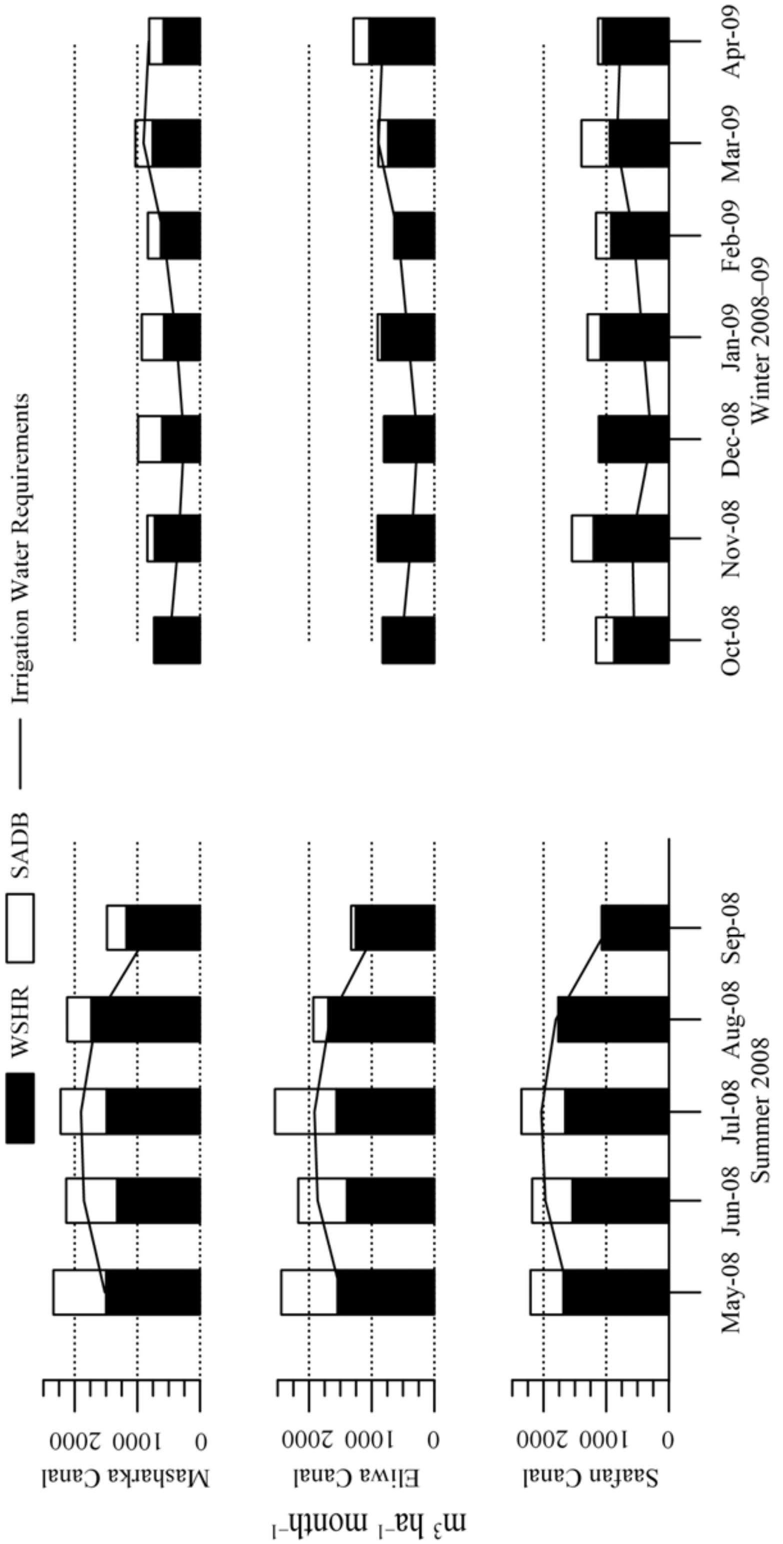


Figure 4. Comparison of water provided from head regulators (WSHR), from WSHR plus reuse of drainage water (SADB), and irrigation water requirements (*IWR*) during the summer of 2008 and the winter of 2008–2009.

Figure 5 shows the water balance for WSHR and WSHR plus SADB for the three branch canals during the summer of 2008 and the following winter. Negative water balance occurred in June and July when only WSHR used, positive water balance occurred in the following months during the summer of 2008 and the winter of 2008–2009. During the summer of 2008, SADB raised the water balance curve upward for the three branch canals indicating effectiveness of using SADB to make up the shortage occurred. Sixty-two (62) % of total WSHR at the winter of 2008–2009 channeled to the drainage canal, SADB should be controlled during oversupply period.

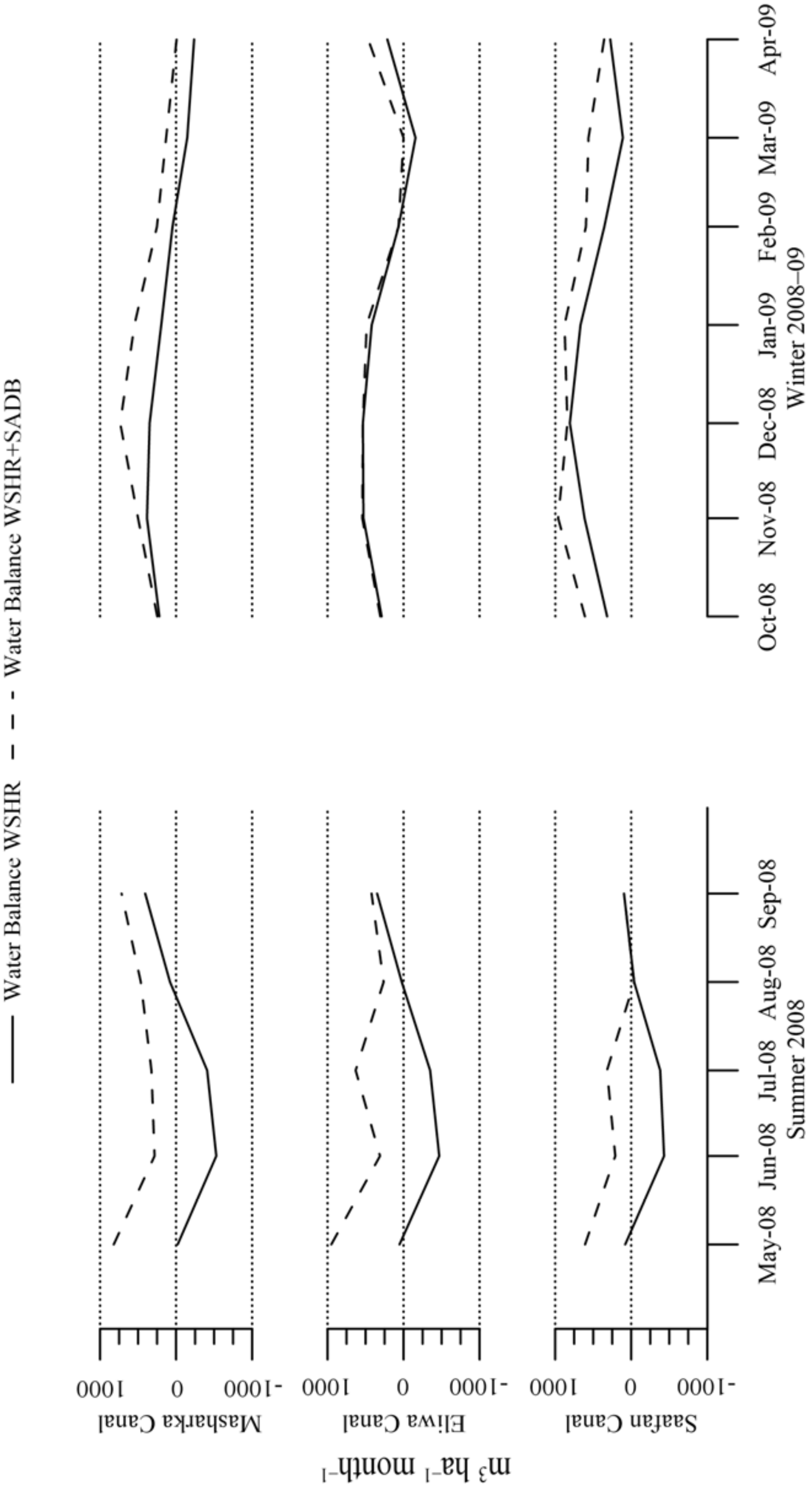


Figure 5. Water balance of water provided from head regulators (WSHR) and WSHR plus reuse of drainage water (SADB) during the summer of 2008 and the winter of 2008–2009.

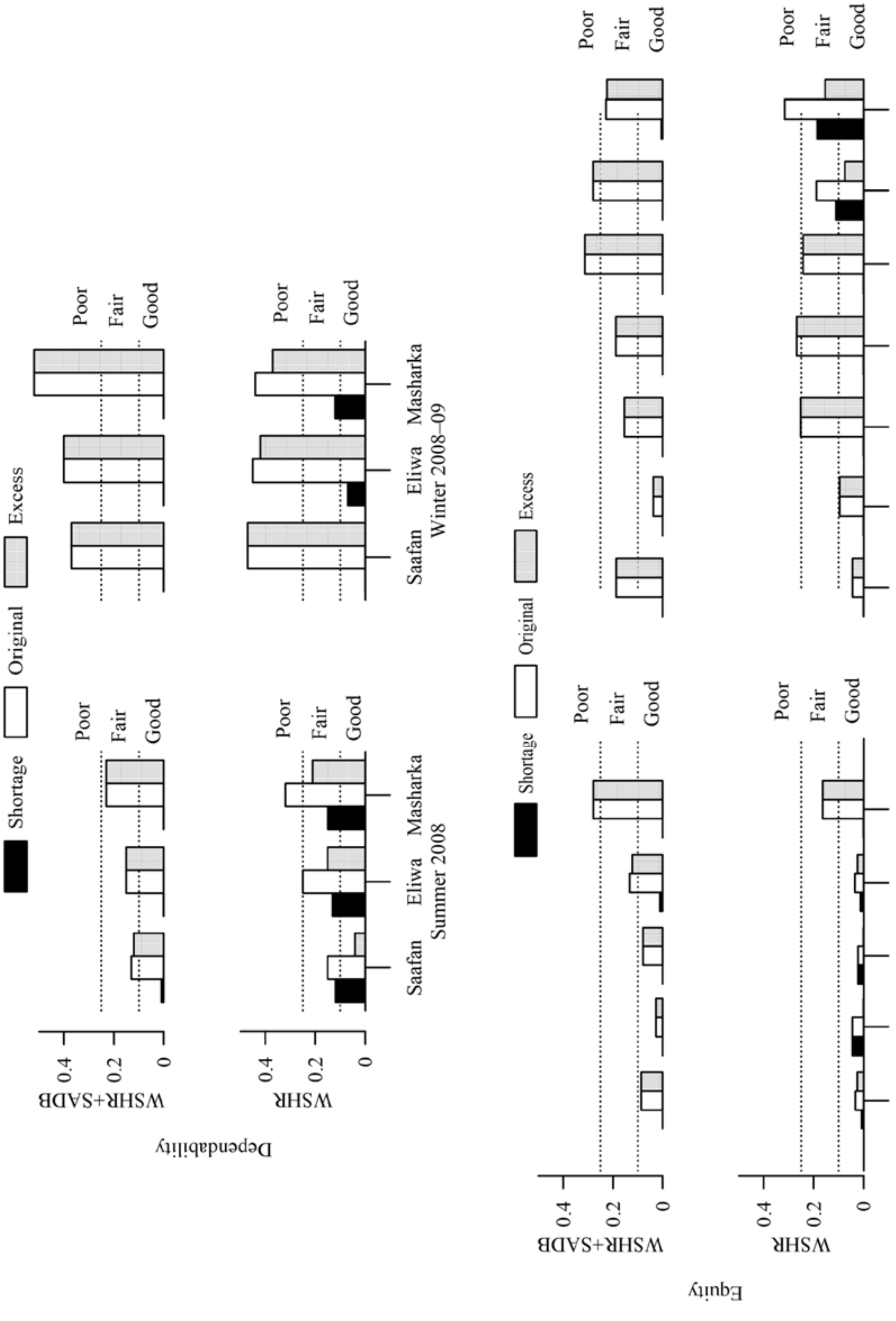


Figure 6. Original and modified equity and dependability based on shortage and excess of water provided from head regulators (WSHR) and WSHR plus reuse of drainage water (SADB) during the summer of 2008 and the winter of 2008–2009.

4.3 Spatial adequacy and equity

During the summer (May–September) of 2008, adequacy for WSHR alone was “poor” in June and July, owing to WSHR shortages occurred at these summer months. The highest *IWR* occurred during these months (Table 5), especially for rice 2,884 m^3 ha^{-1} in June and 2,624 m^3 ha^{-1} in July and rice constituted 56.8% of the crop pattern. If the maximum stipulated area of 50% for rice were strictly applied, it would definitely decrease the *IWR* and improve the adequacy indicator. Adequacy was “good” in May, August, and September. Water supplied was higher in May, August, and September than in June and July, however, *IWR* for June and July were more than those for May, August, and September (Fig. 4). This indicates that upstream users are accelerating to irrigate at June and July owing to the water availability while our study area facing water shortages and farmers have to rely on SADB. The addition of SADB improved adequacy to “good” in June and July.

Equity indicator was “good” during all summer months (Fig. 7). The addition of SADB perfectly improved equity. Values of zero for equity indicator (Fig. 7) mean that SADB counteracted any shortage possibilities. However, original equity indicator will reflect some deficiencies due to variability in water excess among the studied canals. Modified equity indicator clearly shows its applicability when water shortage is the most serious constraint. In some rare cases, when the percentage of shortage are typically the same for the three canals, a value of zero for equity indicator will be obtained, which reveal the uniformity of shortage occurring among the canals.

During the following winter (October–April), adequacy and equity were “good” in all months except for March and April, when the performance was “fair” (Fig. 7), due to high IWR (Fig. 4). This indicates that the water delivery plan used was inadequate. Adding SADB improved adequacy and equity in March and April to “good”.

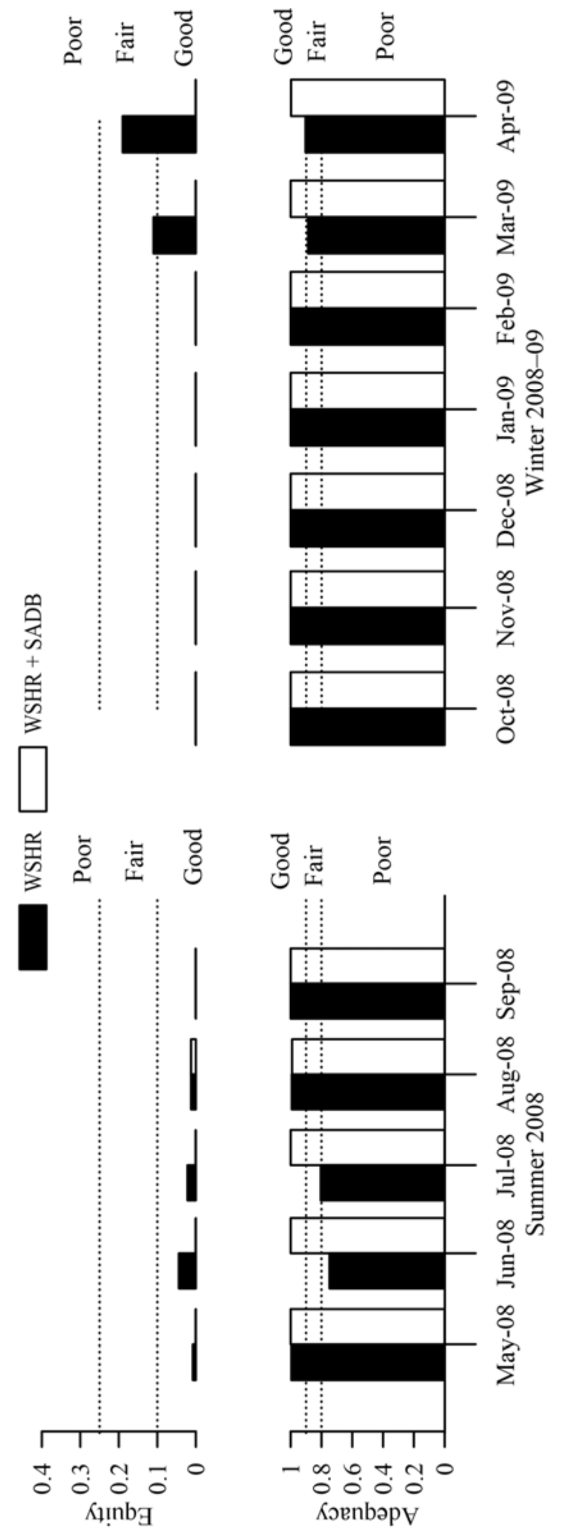


Figure 7. Spatial adequacy and equity of water provided from head regulators (WSHR) and WSHR plus reuse of drainage water (SADB) during the summer of 2008 and the winter of 2008–2009.

4.4 Temporal adequacy and dependability

During the summer (May–September) of 2008, Adequacy and dependability were “fair” for all studied canals (Fig. 8), owing to WSHR shortages occurred in June and July. The addition of SADB improved adequacy and dependability to “good”. Values of zero for dependability indicator (Fig. 8) mean that SADB counteracted any shortage possibilities, although original dependability indicator will reflect some deficiencies due to variability in water excess among the months. Modified dependability indicator clearly shows its applicability when water shortage is the most serious constraint. In some rare cases, when the percentage of shortage are typically the same for all months, a value of zero for dependability indicator can be obtained, which reveal the uniformity of shortage occurring during the study period.

During the following winter (October–April), adequacy based only on WSHR was “good” in all three canals. Dependability was “good” in Saafan and Eliwa canals and “fair” in El-Masharka owing to its position at the tail of the irrigation system. Adding SADB improved adequacy and dependability to “good”.

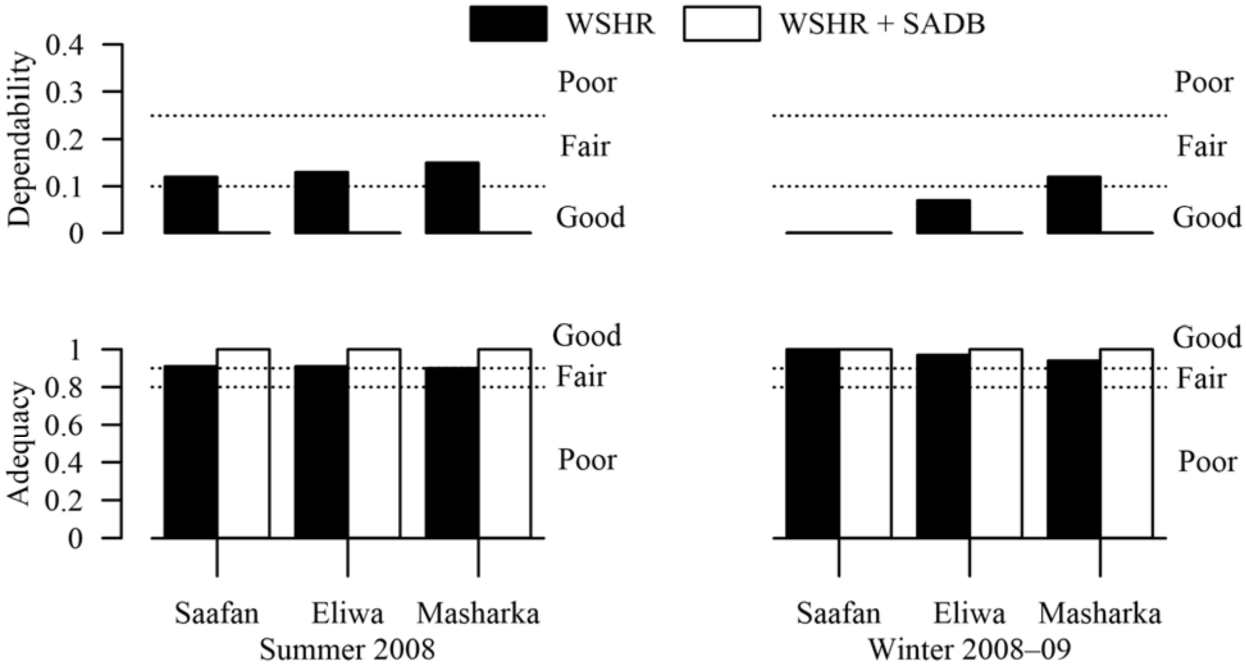


Figure 8. Temporal adequacy and dependability of water provided from head regulators (WSHR) and WSHR plus reuse of drainage water (SADB) during the summer of 2008 and the winter of 2008–2009.

4.5 Average performance indicators

During the summer (May–September) of 2008, and under WSHR conditions, overall adequacy and dependability were “fair” and equity was “good” (Table 6). Overall adequacy and dependability were classed as “fair” not because the yearly water supplied to the study area was inadequate (Fig. 4), but rather because WSHR did not match *IWR* in June and July owing to defects in the water delivery plan. Overall equity was classed as “good” because all three canals received uniform WSHR, despite a deficiency in June and July. The addition of SADB improved adequacy and dependability from “fair” to “good” and equity still improved more.

During the following winter (October–April), overall adequacy, equity, and dependability were “good” under WSHR, and adding SADB improved the values of all three indicators (Table 6). SADB perfectly made up the shortage occurred in the studied canals.

4.6 Modified indicators

Modified dependability and equity indicators showed their applicability in the study area (Fig. 6, Fig. 7, Fig. 8, and Table 6). Under WSHR, they showed better values than those values of original indicators, these values reflects the variability due to the water shortages, any variability due to water excess considered ineffective for our modified indicators. SADB perfectly improved modified dependability and equity during all summer and winter months for all studied canals. Values of zero for those indicators confirm the efficiency of culverts constructed to substitute for the shortage of fresh water supply. Original indicators would not consider variability in water shortage only, but it would consider water excess as well.

There are a number of methodologies that can be used for evaluating and comparing the water delivery performance of irrigation systems. Each methodology has its own advantages and disadvantages, and may be most relevant under particular conditions. This study describes a new methodology for assessing water delivery performance through the use of the concept of modified dependability and equity based on shortage and/or excess. The major advantage of the modified indicators in comparison to the original indicator is that they can be used to represent variation based on excess and/or shortage, while the original indicator is useful for evaluating the variation in excess and shortage.

The utility of the original and modified indicators as performance indicators for comparison of irrigation systems has been illustrated by applying these parameters to an irrigation district in Egypt.

Table 6. Indicator values of water provided from head regulators (WSHR) and WSHR plus reuse of drainage water (SADB) during the summer of 2008 and the winter of 2008–2009.

Indicator	Summer 2008		Winter 2008–2009	
	WSHR	WSHR + SADB	WSHR	WSHR + SADB
Adequacy (P_A)	0.89	1.00	0.97	1.00
Dependability (P_D)	0.13	0.00	0.06	0.00
Equity (P_E)	0.06	0.00	0.04	0.00

4.7 Conclusions and recommendations

The use of SADB was investigated to improve the irrigation system's ability to meet *CWR* by correcting the shortage of water due to the use of WSHR alone in an area in Egypt's Kafr El-Sheikh Governorate. Adequacy, modified dependability, and modified equity indicators were calculated to compare the results based on WSHR use with those based on WSHR plus SADB. During the summer (May–September) of 2008, the use of WSHR plus SADB improved adequacy and dependability from “fair” to “good”, demonstrating that the combined approach has potential. During the following winter (October–April), all indicators were “good” based on WSHR alone, but adding SADB improved them. During the whole study period, the use of WSHR plus SADB perfectly improved overall equity and dependability indicators, which emphasize that SADB successfully supplemented all WSHR shortages, despite the variability in excess water supply. On the basis of this initial evaluation, the effect of this combined approach is studied on the efficiency of water delivery in the study area.

In the study area, the WSHR approach should be modified to improve the management of water distribution. WSHR should match the requirements in June and July. Losses from WSHR during winter (October–April) of 2008–2009 should be utilized instead of losing it into the drainage system. Culverts showed positive effect on improving the shortage occurred on the fresh water supply. However, SADB should be controlled by gates and pumps and used to supply water only when WSHR cannot provide enough water. Farmers' behavior must also be improved, since farmers at the canal's head tend to withdraw more water than they need, leading to shortages at the canal's end. The mixing ratio of SADB water might therefore be higher at the tail of the branch canals. However, if the water quality is sufficiently good, drainage backflow may have the potential to conserve fresh water flowing from the canal head regulators or to increase the area under cultivation.

Modified indicators significantly proofed the validity to be used on the study area, compared to the original indicators, the values of zero showed that all the shortage was effictively supplemented by SADB, compared to the original indicators, these indicators showed fair to poor values owing to the variability of both over supply and shortage. It is recommened that these modified indicators to be used for other study areas based on each study objective.

Our modified indicators were used twice to check the effect of backflow on the values of natural fresh water supply case. Water quality is not studied in this study, but, it would be important to control the backflow to secure the quality of mixed water. Our calibrated equations for WSHR provided a generally good fit to the observed data, direct measurements would improve the accuracy of our calculations.

Chapter 5

Improving water quality by regulating reuse of agricultural drainage water

5.1 Study area and crop pattern

The total study area is 1,946.7 ha; of this, 661.5 ha, 656.5 ha, and 628.7 ha were irrigated by Saafan, Eliwa, and El-Masharka branch canals, respectively, for both summer and winter. Table 7 shows the crop distribution for each canal during the study period. The cultivation pattern did not differ greatly among the three branch canals. Rice and cotton were the main crops cultivated during the summer; collectively, 93% of the area is cultivated with these water-intensive crops. Water consumption by these crops and “other” crops represent almost twice the water consumption for maize (Table 5). This explains the high *CWR* in the summer compared to the winter, as shown in Table 8. Farmers are free to decide the crops to cultivate in their fields, and rice is considered as a high value crop, so they frequently exceed the government’s stipulated maximum limit of 50% area under rice (as a water conservation measure due to high water consumption by paddy rice (WAGS 2008)). Stricter monitoring of farmers activities and more effective crop management policies are required (Arafat et al. 2010).

The main crops in winter were wheat, alfalfa, and sugar beet, collectively accounting for 94% of the area cultivated. Water consumption by the main winter crops was almost half that of cotton and rice; therefore, water requirements in the winter were low compared to requirements in the summer (Table 6). Water consumption by “other” crops was much lower than that of the three main crops. Crop compositions are random along the canals; but, the quality of water along these canals is deteriorating towards their ends. Studies conducted by MWRI, irrigation with saline water (1,000 mg L^{-1}) showed a reduction in yields of up to 29% compared to fresh water irrigation, and yield declines were most marked for sensitive crops like maize and alfalfa in comparison to more tolerant crops like cotton and wheat, which can cope with a higher salinity (Abdel-Dayem et al. 2007). Therefore, for most farmers, saline irrigation water means lower yields. Alfalfa is considered as a salt-sensitive crop, and it represents 30% of the area cultivated in the winter. Hence, significant amount of alfalfa crop is subjected to saline water, and not only in the study area but also over a million acres in the delta depend either partially or entirely on drainage water for irrigation (NAWQAM 1999). Stricter measures should be taken to redistribute the crops along the canals based on their sensitivity to salinity, as this would increase the yield and profit from the crops cultivated.

Table 7. Irrigated cropping pattern during the summer of 2008 and the following winter.

	Crops (%)	Saafan Canal	Eliwa Canal	El-Masharka Canal
Summer 2008	Rice	55	57	58
	Cotton	33	36	35
	Maize	5	6	5
	Other	7	1	2
	Total	100	100	100
	Area (ha)	661.5	656.5	628.7
Winter 2008–2009	Wheat	38	37	34
	Alfalfa	32	28	32
	Sugar beet	23	29	26
	Other	7	6	8
	Total	100	100	100
	Area (ha)	661.5	656.5	628.7

5.2 Water supply and water requirements

Fresh water supply, agricultural drainage backflow, and *IWR* during the summer of 2008 and the following winter are listed in Table 8 for the three branch canals. This table permits two important comparisons: fresh water supply versus *IWR*, and fresh water supply plus backflow versus *IWR*. Water supplied was greater in summer than in winter, as *CWR* for summer crops were more than those for winter crops (Table 8). Farmers have been free to decide what crops they wish to plant and many farmers have turned towards profitable but water-intensive crops like rice as shown in Table 5. In the summer, some farmers cannot irrigate their land because not enough water flows down to their irrigation canals. A national survey indicated that 71% of farmers find the water in their irrigation canals to be insufficient during summer months, when pressure on water supplies is most intense (El-Zanaty 2001). Rice was considered as the most water-intensive crop in the study area and the higher water requirements occurred in June and July as shown in Table 5.

During the summer, if only the fresh water supply was used, water excess occurred in September and deficiency occurred in June and July. The additional water supplied by backflow, occurring at all months, boosted the water supply but was required to augment the shortage of fresh water supply only in June and July. The fresh water supply in June and July for the three branch canals was less than that in May and August, while requirements for irrigation water was higher (Table 8). The shortage was due to an ineffective water delivery plan and intensive water use by upstream users to meet the high water consumption at these months. The total fresh water supply for each of the three branch canals was somewhat lower than the requirements; however, backflow was more than sufficient to counteract the shortage of fresh water supply.

During the winter, an excess of fresh water was supplied to the three branch canals at most times, this was to secure a hydraulic head required for gravity irrigation for winter crops under canal systems with large conveyance capacity designed to provide maximum water requirements of the water-consuming summer crops in the extremely flat topography. This indicates a lack of utility of any backflow supply except for the Eliwa canal during March and for the El-Masharka canal during March and April. However, backflow occurred in most months. The total fresh water supply for each of the three branch canals was approximately 60% greater than the requirements, and backflow raised the water supply to approximately twice of the requirements. This situation deteriorates water quality.

Farmers channel the vast majority of Nile water (90%) to cultivate their fields and any water not taken up by growing crops infiltrates the soil and passes into the drainage system. A recent assessment at the main canal level showed that 53% of the annual irrigation water supply entered drainage systems and saline groundwater sinks, indicating an oversupply (El-Agha et al. 2011). This waste of water can only be reduced if farmers are motivated not to demand more water than necessary (Vandersypen et al. 2006). In the study area, 27% of water was channeled out in the culvert to the drainage canal during the summer, and 82% during the winter. Water excess over water requirements means that backflow channeled in the pipe as a supplement is simply drained back again into the drainage canal after mixing with the canal fresh water, leading to an unnecessary loss of the fresh water and deterioration of the canal water quality.

Table 8. Fresh water supply, backflow, and requirements during the summer of 2008 and the following winter.

Season	Month	Saafan Canal			Eliwa Canal			El-Masharka Canal		
		Fresh water supply	Fresh water supply + Backflow	Water requirement	Fresh water supply	Fresh water supply + Backflow	Water requirement	Fresh water supply	Fresh water supply + Backflow	Water requirement
			m^3 ha^{-1}			m^3 ha^{-1}			m^3 ha^{-1}	
Summer 2008	May	1,681	2,209	1,602	1,546	2,443	1,492	1,499	2,340	1,520
	June	1,538	2,180	1,970	1,394	2,173	1,863	1,324	2,136	1,853
	July	1,654	2,354	2,035	1,564	2,544	1,913	1,491	2,224	1,900
	Aug.	1,766	1,766	1,804	1,693	1,932	1,669	1,737	2,121	1,656
	Sept.	1,068	1,068	973	1,255	1,328	907	1,175	1,486	768
	Total	7,707	9,577	8,384	7,451	10,419	7,843	7,225	10,306	7,697
Winter 2008–2009	Oct.	870	1,162	551	809	828	521	706	734	486
	Nov.	1,199	1,546	583	890	906	363	722	840	340
	Dec.	1,086	1,119	277	803	803	268	603	989	254
	Jan.	1,086	1,296	417	838	905	419	576	929	381
	Feb.	919	1,162	564	641	641	575	627	832	580
	Mar.	942	1,394	830	735	893	892	754	1,032	901
	Apr.	1,051	1,132	774	1,038	1,290	825	580	811	817
	Total	7,155	8,811	3,996	5,755	6,265	3,862	4,568	6,167	3,759

5.3 Water supply ratio

Calculated values for the water supply ratio (*WSR*) are listed in Table 9. During the summer, when only the fresh water supply was used, the average *WSR* values were less than 1 (0.92, 0.95, and 0.94) for the three branch canals, while additional water supplied by backflow raised values to greater than 1 (1.14, 1.33, and 1.34) respectively. These values indicate two important points: the first is that backflow increased the water supply by 40% while only 9% was required, and backflow occurred during all summer months while it was required only in June and July. The second is that fresh water waste occurred to a significant degree in the system, as backflow was mixed with the fresh water supply and channeled out again in the culvert to the drainage canal. During the winter, when only the fresh water supply was used, the *WSR* values were greater than 1 (1.79, 1.49, and 1.22) for the three branch canals, while additional water supplied by backflow raised the values (2.2, 1.62, and 1.64). These values indicate that backflow increased water supply by more than 100%, even though there was no need of the backflow. Also, fresh water waste occurred to a significant degree in the system, as the fresh water supply was mixed with backflow and channeled out again unused into the pipe to the drainage canal.

Table 9. *WSR* values during the summer of 2008 and the following winter.

Season	Month	Saafan Canal		Eliwa Canal		El-Masharka Canal	
		WSR Fresh water supply	*WSR* Fresh water supply + Backflow	*WSR* Fresh water supply	*WSR* Fresh water supply + Backflow	*WSR* Fresh water supply	*WSR* Fresh water supply + Backflow
Summer 2008	May	1.05	1.38	1.04	1.64	0.99	1.54
	June	0.78	1.11	0.75	1.17	0.71	1.15
	July	0.81	1.16	0.82	1.33	0.78	1.17
	Aug.	0.98	0.98	1.01	1.16	1.05	1.28
	Sept.	1.10	1.10	1.38	1.46	1.53	1.93
	Average	0.92	1.14	0.95	1.33	0.94	1.34
Winter 2008–2009	Oct.	1.58	2.11	1.55	1.59	1.45	1.51
	Nov.	2.06	2.65	2.45	2.50	2.13	2.47
	Dec.	3.92	4.04	3.00	3.00	2.37	3.89
	Jan.	2.60	3.11	2.00	2.16	1.51	2.44
	Feb.	1.63	2.06	1.11	1.11	1.08	1.43
	Mar.	1.13	1.68	0.82	1.00	0.84	1.15
	Apr.	1.36	1.46	1.26	1.56	0.71	0.99
	Average	1.79	2.20	1.49	1.62	1.22	1.64

5.4 Impact on salinity

Salinity measurements of water are shown in Fig. 9 for the three branch canals during the summer of 2008 and the following winter. This figure shows two salinity values along the studied canals: one curve shows salinity values as measured at the field representing the use of the total mixed water of fresh water and total backflow water. The second curve shows calculated salinity values representing the use of the mixed water of fresh water and part of backflow water to be supplemented to supply the deficit of fresh water (Fig. 9). Due to the actual field conditions and existing culverts connecting the canal end with the drainage canal, water salinity is increasing towards the end of the canal. The most fortunate farmers are those who have no need for drainage water in the first place, as they have enough good quality irrigation water. Whereas, those at the end of the canals have access to enough water, but of bad quality caused by mixing of drainage water, as drainage water is different in quality to irrigation water. When water passes through the soil and drainage network, it picks up salts, agricultural chemicals, and other pollutants. Drainage water is not only a substandard source but a symbol of marginality (Barnes 2012a).

During the summer, backflow occurred during all summer months and exceeded the requirements. Based on the actual field measurements, the salinity level increased from 400 mg L^{-1} and reached values of 1,000 mg L^{-1} that could cause slight to moderate problems to the crops, especially for sensitive ones like maize and most vegetables. Backflow deteriorated the water quality unnecessarily. Control of the backflow according to the actual requirements would improve the water quality. The amount of unutilized backflow was calculated, as shown in Table 10. During May, August, and September, 100% of the backflow was unutilized, while, in June and July, some of the backflow was still unutilized. The salinity values were calculated based on the utilized backflow while omitting any effect of unutilized flows, as shown in Fig. 9. Water salinity values compared to actual measurements at the end of the canal showed an improvement in salinity by 30% in June and July and 100% in May, August, and September.

During the winter, backflow was not required for any winter months; however, it still occurred. Based on the actual field measurements, the salinity deteriorated from 400 mg L^{-1} and reached values of 1,000 mg L^{-1} that could cause slight to moderate problems to crops especially the sensitive ones like alfalfa and most vegetables. Backflow therefore also deteriorated the quality unnecessarily in the winter. Again, control of the backflow would improve the water quality. The unutilized backflow were calculated, as shown in Table 10. During all winter months, 100% of the backflow was unutilized, except in March for the El-Masharka canal, where only some of the actual backflow was unutilized (Table 10). The salinity values were calculated based on utilized backflow while omitting any effect of unutilized flows, as shown in Fig. 9. Salinity values compared to actual measurements at the end of the canal reduced by 100%. Using utilized backflow decreased the water salinity to values of less than 500 mg L^{-1}, except in June and July were little more than 500 mg L^{-1}. The recycling of the saline and often polluted drainage water impacts the quality of water flowing through Egypt’s irrigation network. A farmer who can access a better quality of water for irrigation will achieve higher yields and profits. Irrigation with saline water is possible while still maintaining good levels of production (so-called ‘‘biosaline agriculture’’), but this requires careful land management practices, which although already piloted, have yet to become widespread throughout the country (EL-Bably 2002; Abdelly et al. 2008).

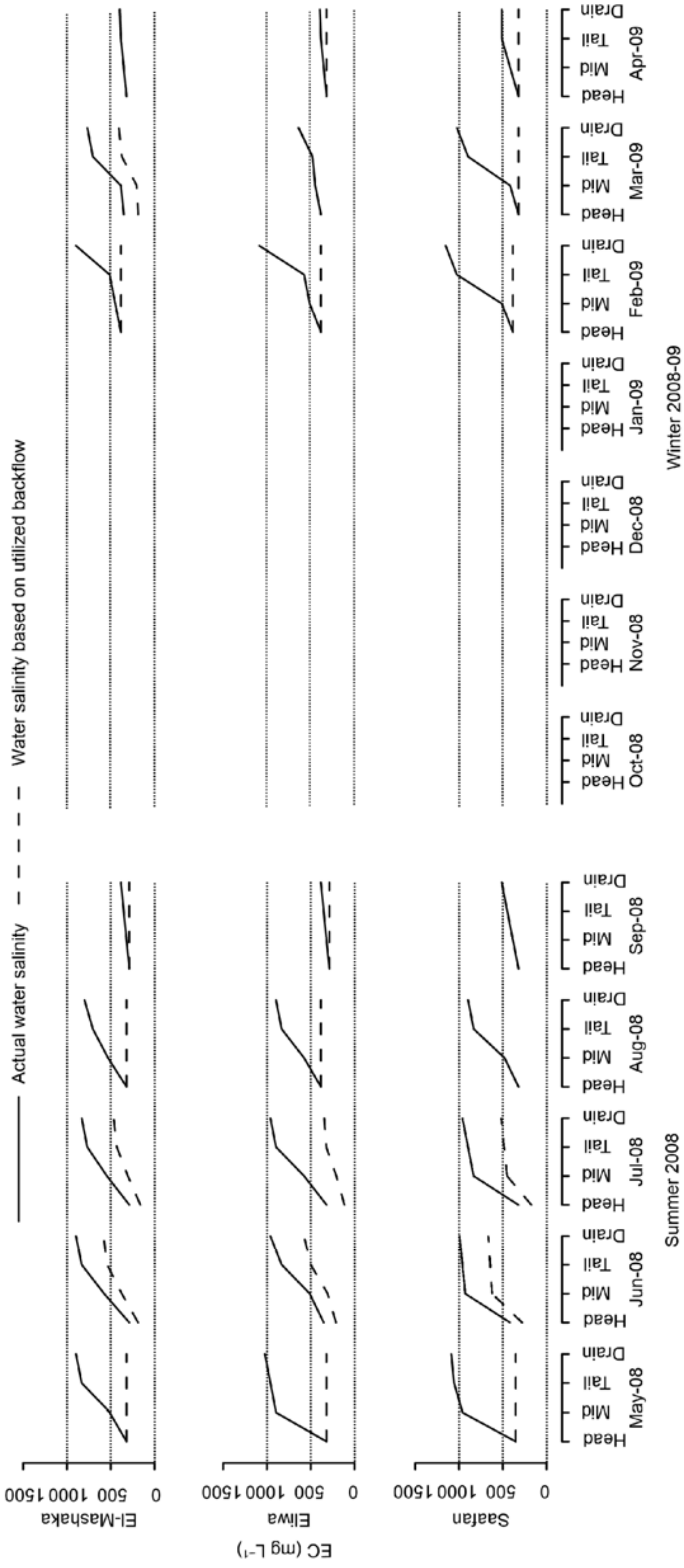


Figure 9. Actual water salinity and those based on utilized backflow (mg L^{-1}) during the summer of 2008 and the winter of 2008–2009.

Table 10. Relative unutilized bckflow as a percentage of total backflow during the summer of 2008 and the following winter.

Season	Month	Saafan Canal	Eliwa Canal	El-Masharka Canal
		Unutilized Backflow (%)	Unutilized Backflow (%)	Unutilized Backflow (%)
Summer 2008	May	100	100	100
	June	33	40	35
	July	46	64	44
	Aug.	0	100	100
	Sept.	0	100	100
	Average	64	87	85
Winter 2008–2009	Oct.	100	100	100
	Nov.	100	100	100
	Dec.	100	100	100
	Jan.	100	100	100
	Feb.	100	100	100
	Mar.	100	0	47
	Apr.	100	100	0
	Average	100	100	100

5.5 Conclusions and recommendations

The efficiency of using backflow to supplement the fresh water irrigation and its effect on water quality in Kafr El-Sheikh Governorate were investigated. The water supply ratio (*WSR*) were calculated as an indicator to compare the results based on fresh water use with those based on fresh water plus backflow. During the summer (May–September) of 2008, backflow significantly deteriorated water quality, while it was actually required only in June and July only to make up the shortage, not to exceed the requirements. During the following winter (October–April), water availability was generally sufficient from the fresh water supply; however, drainage backflow occurred and unnecessarily deteriorated the water quality. The use of fresh water supply plus backflow perfectly supplemented all fresh water supply shortages; however, the backflow exceeded the requirements. Therefore, control of the backflow according to the actual requirements would improve the water quality. An improvement of over 30% in June and July was realized, and 100% improvement was realized in May, August, September, and all winter months.

Excessive backflow and high water levels in the main drain indicate that upstream users withdraw more water than they need, exceeding the crop consumption, and unused water was drained out to the drainage canals. Therefore, our study area faced shortages of freshwater supply and excessive saline backflow. The freshwater supply approach used in the area should therefore be modified to improve the management of water distribution. The farmers must also be motivated not to demand more than necessary. The canal systems were designed to provide the maximum water requirements of the water-consuming summer crops, but this has led to an excess freshwater supply in the winter. Further measures should be considered to improve the management of water distribution.

Cropping pattern along the canals indicates random cultivation of crops, as farmers are free to decide which crops to cultivate. The mixing ratio of saline backflow water is higher at the end of the branch canals. Here, a better organized cropping pattern should be adopted based on the salt tolerance of each crop (i.e., sensitive crops should be planted at the canal's head and tolerant crops at the end).

Our calibrated equations for fresh water supply and HEC-RAS calculations for backflow provided a generally good fit to the observed data, but direct measurements would improve the accuracy of the calculations.

Chapter 6

Summary, conclusion and recommendations

6.1 Summary

The use of SADB to improve the irrigation system's ability to meet crop water requirements (*CWR*) was firstly investigated. SADB augment the shortage of water due to the use of WSHR alone in an area in Egypt's Kafr El-Sheikh Governorate. In the first part of this study, adequacy, modified dependability, and modified equity indicators were calculated to compare the results based on WSHR use with those based on WSHR plus SADB. In the second part of this study, the efficiency of using backflow to supplement the fresh water irrigation were investigated and its effect on water quality in Kafr El-Sheikh Governorate. The water supply ratio (*WSR*) as an indicator were calculated to compare the results based on fresh water use with those based on fresh water plus backflow.

6.2 Conclusion

During the summer (May–September) of 2008, the use of WSHR plus SADB improved adequacy and dependability from "fair" to "good", demonstrating that the combined approach has potential. During the following winter (October–April), all indicators were "good" based on WSHR alone, but adding SADB improved them. During the whole study period, the use of WSHR plus SADB perfectly improved overall equity and dependability indicators, which emphasize that SADB successfully supplemented all WSHR shortages, despite the variability in excess water supply.

During the summer (May–September) of 2008, backflow significantly deteriorated water quality, while it was actually required only in June and July and only to make up the shortage, not to exceed the requirements. During the following winter (October–April), water availability was generally sufficient from the fresh water supply; however, drainage backflow occurred and unnecessarily deteriorated the water quality. The use of fresh water supply plus backflow perfectly supplemented all fresh water supply shortages; however, the addition of backflow caused excess of the requirements. Therefore, control of the backflow according to the actual requirements would improve the water quality. An improvement of over 30% in June and July was realized, and 100% improvement was realized in May, August, September, and all winter months.

6.3 Recommendations

The following points were recommended from this study.

1. The canal systems were designed to provide the maximum water requirements of the water-consuming summer crops, but this has led to an excess freshwater supply in the winter. Further measures should be considered to improve the management of water distribution.
2. Losses from WSHR especially during winter (October–April) of 2008–2009 should be utilized instead of losing it into the drainage system.

3. Culverts showed positive effect on improving the shortage occurred on the fresh water supply during summer. However, SADB should be controlled by gates and pumps and used to supply water only when WSHR cannot provide enough water.
4. The mixing ratio of SADB water might be therefore higher at the tail of the branch canals. However, if the water quality is sufficiently good, drainage backflow may have the potential to conserve fresh water flowing from the canal head regulators or to increase the area under cultivation.
5. Modified indicators significantly proved the validity to be used on the study area, compared to the original indicators, the values of zero showed that all the shortage was effictively supplemented by SADB, compared to the original indicators, these indicators showed fair to poor values owing to the variability of both over supply and shortage. It is recommened that these modified indicators to be used for other study areas based on each study objective.
6. The calibrated equations for fresh water supply and HEC-RAS calculations for backflow provided a generally good fit to the observed data; however direct measurements would improve the accuracy of the calculations.
7. The WSHR approach should be modified to improve the management of water distribution, and should match the requirements.

8. Excessive backflow and high water levels in the drainage canal indicate that upstream users withdraw more water than they need, exceeding the crop consumption, and unused water was drained out to the drainage canals. Therefore, in our study area, farmlands at the end of the system face freshwater supply shortages and excessive saline backflow.
9. The farmers must also be motivated not to demand more than necessary. Their behavior must also be improved, since farmers at the canal's head tend to withdraw more water than they need, leading to shortages at the canal's end.
10. Planning a suitable cropping pattern particularly at the end of the irrigation system in the Nile Delta is vital measure to save water for downstream users.
11. Farmers exceed the limit for rice cultivation, 56.8% of the cropping area, more than the government's stipulated maximum of 50%. They should organize the cropping pattern among t to ensure obeying rules from the government.
12. Cropping pattern along the canals indicates random cultivation of crops, as farmers are free to decide which crops to cultivate. More controlled measures must be taken to ensure equitable distribution of crops
13. The mixing ratio of saline backflow water is higher at the end of the branch canals. Thus, a better organized cropping pattern should be adopted based on the salt tolerance of each crop (i.e., sensitive crops should be planted at the canal's head and tolerant crops at the end).

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Summary in Japanese

ナイルデルタにおいて農家が主に直面する問題は、灌漑システムの下流および末端での水不足である。近年の水需要の増大に伴い、この問題は悪化している。現在、エジプトの水資源灌漑省では、農業排水を再利用することで供給水量の不足を補う取組がされている。Kafr El-Sheikh 行政区では、農業排水を再利用(SADB)するために幹線排水路と用水路末端を管で接続する工事を実施した。しかし、排水路から用水路への流入量は水頭差で決まり、制御できない構造となっている。エジプトでは、公的管理の揚水機場と農家の私的管理による小規模ディーゼルポンプによって、排水路の水を用水路へ汲み上げて農業に再利用する。この排水再利用により、国が利用できる水資源は 12.6%増加した。しかし、排水は土壌や排水路網を浸透・流下する過程で、塩類、農薬やその他の汚濁物質を吸収する。そのため、排水と用水の水質は大きく異なり、排水が用水に混ざることで、用水の水質は悪化する。エジプトでは一般に、混合後の塩分濃度が 1,000 mg L^{-1} 程度以下に収まるように排水を用水に混合させている。

以上のことから、農業排水の再利用を行う灌漑用水路網の実効評価と再利用規制による水質改善をテーマとして研究を行った。本論は主に以下の 2 つのサブテーマから構成される。

１．用水不足対策としての排水再利用の実効評価を充足率，信頼性，平等性の点から行った。分析には WSHR（用水のみ）と WSHR＋SADB（用水と排水再利用）の両者について行った。2008 年の夏季（5 月～9 月）の 2 つの月において SADB（排水再利用）は充足率を大きく改善したことが示され，充足率と信頼性の評価は「普通」から「良好」となった。続く冬季（10 月～4 月）においては，SADB は 3 月，4 月のみ充足率と平等性を改善した。これは、冬季において十分な灌漑用水が供給されるからである。

２．補助灌漑水源としての排水再利用の効果とそれが水質に及ぼす影響ーKafr El-Sheikh 行政区の事例ー分析には水供給率（*WSR*）の指標を用いた。2 つの水供給状態（1）用水供給のみ（2）用水供給と排水再利用について調べた。2008 年の夏季の間、*WSR* は 0.93、排水の再利用を加えると 1.27 であった。続く冬季の間では、*WSR* は 1.50 を示し、排水の再利用を加えると 1.82 にとなった。調査対象用水路の上流、中流、末端、排水路の 4 か所で水の塩分濃度を測定した結果、塩分濃度は水路の上流から下流に向かって著しく増加した。過剰な排水路からの逆流は水質の最も深刻な制限要因である。そこで、排水の逆流による用水の塩分濃度の影響を定量的に評価した結果、再利用の規制によって塩分濃度が改善されることが示された。夏季における排水の逆流は水質を著しく悪化させたが、実際には、必要量を超えないように不足分を補うためには、6 月と 7 月のみ排水を逆流させる必要があることが示された。冬季（10-4 月）においては、用水供給量は概ね十分であった。しかし、排水の逆流は生じており、不要な水質悪化を招いたことが示された。もし排水の逆流が実際の必要水量に応じて管理されるのであれば、水質は改善されることが示唆された。6 月と 7 月には、水の塩分濃度は 30%以上改善されており、5 月、8 月、9 月、そして冬の全ての月においては十分な用水供給があるので、排水の再利用は不要であり、100%まで改善されることが示された。

本地区で行われている用水供給は、水配分を改善するために修正が必要である。水路上流の農家は必要水量以上に多くの水を取水し、これが水路下流の水不足につながるので、農家の水利用も改善が求められる。水路網は夏季の水需要のピークに合わせて設計されているが、これは冬季における過剰な用水供給につながる。水配分管理を改善するための更なる対策が必要である。排水の再利用は分水ゲートやポンプによって管理されなくてはならない。また、それは用水供給が不十分なときにのみ行われるべきである。排水の混合割合は支線水路の下流端で高くなる。しかし、水質が良好であれば、排水の再利用は水路上流の分水工からの貴重な淡水の保全や耕作面積の増加につながる。

List of related papers

Khater, A., Kitamura, Y., Shimizu, K., Abou El Hassan, W. and Fujimaki, H. 2014. Quantitative analysis of reusing agricultural water to compensate for water supply deficiencies in the Nile Delta irrigation network. Paddy and Water Environment. DOI 10.1007/s10333-014-0454-y. 2014 (Published online: 30 July 2014).

This article mainly covers Chapter 4 of the thesis.

1. Khater, A., Kitamura, Y., Shimizu, K., Somura, H. and Abou El Hassan, W. 2014. Improving water quality in the Nile Delta irrigation network by regulating reuse of agricultural drainage water. Journal of Food, Agriculture & Environment (JFAE). Vol. 12, (3&4): 329-337, 2014.

   This article mainly covers Chapter 5 of the thesis.

International conferences

1. Khater, A., Kitamura, Y. and Shimizu, K. 2011. Evaluation of Water Delivery Performance in Irrigation Networks Affected by Backflow from Drainage in the lower Nile Delta. 8th International AFAS Joint Symposium between Japan and Korea. (Nov.16-17, 2011), Yonago, Japan.
2. Khater, A., Kitamura, Y., Shimizu, K. and Abou El Hassan, W. 2013. Impact of drainage on water delivery performance in irrigation networks at the lower Nile Delta. Eleventh International Conference on Dryland Development "Global Climate Change and its Impact on Food & Energy Security in the Dry Lands" 18-23 March 2013, Beijing, China.
3. Khater, A., Kitamura, Y., Shimizu, K., Somura, H. and Abou El Hassan, W. 2014. Improving water quality in the Nile Delta irrigation network by regulating reuse of agricultural drainage water. "2nd Annual International Conference on Water" 14-17 July 2014, Athens, Greece.