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# Salinity dynamics of wetland ditches receiving drainage from irrigated agricultural land in arid and semi-arid regions

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ABSTRACT

Agricultural drainage ditches are considered as wetland ecosystems when they possess the characteristic hydrology, soil and vegetation of wetlands. In arid and semi-arid regions, wetlands receiving agricultural drainage have to cope with the conservative nature of salts leached from soils. Excessive accumulation of salts in wetlands may threaten the ecological functions of the system, thus endanger the sustainability of the drainage disposal system and the productivity of the farmlands. Based on the salt and water balance in a farmland drainage and wetland disposal system in arid regions, this paper presents a thorough investigation on salinity dynamics of wetland ditches receiving agricultural drainage. Theoretical equations were derived to describe salinity changes in water and soils of wetlands under both equilibrium and pre-equilibrium conditions; a case example was then used to display model predictions of salinity variations over time under different salinity management goals. The example wetlands are de facto drainage ditches that possess wetland characteristics, and the ditch to farmland area ratio is 9.1%. The results showed that salt as a conservative substance will eventually concentrate in the ditches to a very high level if there is little outflow discharge; but the salt accumulation process may develop over a relatively long time, which opens a time window for management practice, such as flushing the salts when fresh water is available. By assuming different threshold salinity levels in the ditches, the proposed analytical models were used to predict time intervals when fresh water recharge is needed to bring down the salinity level in the ditches. For the study area under current drainage practice, the predicted outflow to inflow ratio for salinity was 58.2% and reached an equilibrium level of 9.60 $g\,L^{-1}$ in the ditches; salinity levels in the ditches reached threshold values of 5, 7 and 9 $g\,L^{-1}$, in about 1, 4 and 12 years, respectively. Salinity analysis showed that the salt retention capacity of the ditch soil is limited, the soil salinity varied according to the ditch water; salt removal through plant uptake and harvest was insignificant. This study indicates that although salt concentration in wetlands receiving agricultural drainage may eventually build up to a critical level, timely recharge with fresh water may bring down salt content in the wetlands and sustain adequate environmental and ecological functions of such a drainage disposal system in arid and semi-arid regions.



## 1. Introduction

Agricultural drainage systems are mainly designed for salinity control in arid and semi-arid regions. Because drainage water contains agricultural nutrients and other chemicals leached from soils, drainage discharge has been blamed as a major contributor of agricultural non-point pollution (Evans et al., 1995; Skaggs et al., 1994). Numerous studies have been conducted worldwide in search for effective measures to mitigate the adverse impact of agricultural drainage. Among the measures proposed, constructed or restored wetlands have been found more economical and sustainable than other approaches in terms of management and operations (Verhoeven et al., 2006; Mitsch and Day, 2006). Mitsch and Day (2006) suggested that wetland areas in agricultural regions should cover 3–5% of the whole catchment in order to be effective in flood control and water quality improvement; Verhoeven et al. (2006) suggested a wetland ratio of 2–7% based on studies carried out in the U.S., Sweden and China. In agricultural landscape where free space for constructing wetlands is limited, open drainage ditches can be maintained to possess wetland characteristics and provide certain ecological services (Kröger et al., 2009). The ditches that drain too fast or do not stay wet for a certain period during the growing season cannot be regarded as legitimate wetlands; only those properly managed ditches, which hold agricultural drainage water

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long enough to produce wetland hydrology and provide ecological services, can be considered as a particular form of wetland.

In arid and semi-arid irrigation areas, long standing of water in drainage ditches results in great water loss through evapotranspiration and a simultaneous increase in salt concentration. When salinity in wetlands reaches threshold levels, there is potential of causing various environmental and ecological problems (Jolly et al., 2008; Lamontagne et al., 2006; Nielsen et al., 2003; Nielsen and Hillman, 2000). Huckelbridge et al. (2010) modeled salt dynamics and vegetation changes of a wetland receiving salt-laden agricultural drainage water in the Colorado River Delta. Their predictions for hypothetical scenarios showed that increase in salinity and/or decrease in inflow would result in significant decrease of vegetation cover, which would pose a threat to the habitat and reduce the ecological value of the wetland.

Currently, no consensus on the threshold level of wetland salinity exists (Nielsen et al., 2003; Nielsen and Hillman, 2000). Salinity classification defines that salt concentration of fresh water is less than 0.5 g L$^{-1}$; brackish water between 0.5 and 30 g L$^{-1}$; saline water between 30 and 50 g L$^{-1}$; and brine more than 50 g L$^{-1}$. Because a wetland has various biomes, different tolerance levels to salinity exist (Thiere et al., 2009; Nielsen and Hillman, 2000). Research conducted in Australia revealed some of the impacts that salinity has on biomes (Meredith and Beesley, 2009; Dixon, 2007; Nielsen et al., 2003; Clunie et al., 2002). Some of the biotic groups were found adaptable to the elevated salinity level and have very high tolerance to salt concentrations (Huckelbridge et al., 2010; Huckelbridge, 2008). Although some researchers reported that a salinity level up to 1–2 g L$^{-1}$ may affect wetland ecology (Clunie et al., 2002; Nielsen and Hillman, 2000), the majority of the studies have shown that limiting the salinity level to 8–10 g L$^{-1}$ can maintain the normal life cycle of wetland plants, fishes and some key biomes (Huckelbridge, 2008; Clunie et al., 2002).

While bounteous literature exists on the use of wetlands to remove degradable or retainable pollutants including nitrogen, phosphorus and sediments, few studies have fully addressed the problems of wetlands receiving salt-laden drainage water in arid and semi-arid regions; it is not clear how fast salt accumulation in these wetlands may reach a level endangering their ecological function, and what management options can be taken to sustain the wetland eco-system. There are variable paths for fate and transport of salts in a wetland system. A few researchers suggested that salts may be removed from the system by harvesting wetland plants, such as reeds (*Phragmites australis*) (Li et al., 2008; Lan et al., 2003), but their findings on removal rates are not consistent and the proposed methods are not economically feasible. Plant uptake of salts from wetlands is generally considered as insignificant. The wetland soils are another potential salt sink. Some studies indicate that a growing amount of organic matter in wetland soils may absorb or immobilize more salts, but the soluble nature of salts makes the soils only a temporary exchange site other than a permanent residing place. Moreno-Mateos et al. (2008, 2010) studied water quality changes through variably sized wetlands constructed on abandoned farmlands due to soil salinization in a semi-arid climate. They found that while salts may be temporarily stored in sediments during the drying periods, the following wet cycle can readily release the salts to the water body.

Once the wetland salinity has breached a critical level, artificial irrigation and freshwater recharge are two commonly adopted management practices to lower salinity levels (Lamontagne et al., 2006; Meredith and Beesley, 2009; Quinn, 2009). Fresh water availability and economic feasibility are primary considerations for proper management options. Lamontagne et al. (2006) studied salt dynamics of a wetland used as an agricultural drainage disposal site, in which elevated salinity level (electrical conductivity greater than 100 mS cm$^{-1}$) caused a foul smell from the site. They observed that the wetland salinity was reduced by 2/3 after a flooding event in the nearby river; but high salinity level resumed in about one month as the result of salt concentration under high evaporation at the site. Nielsen and Hillman (2000) discussed various scenarios of water and salt interactions among uplands, wetlands and rivers. They pointed out that disposing salt into the wetlands during the low flow period should be carefully timed; dispersed, pulse discharges may provide time windows for the disposal sites to recover from high salinity levels. Their prediction for salinity rise over a threshold level in Australian rivers put the time frame up to 100 years.

In order to examine the process of salinity dynamics over time in wetlands, this paper presents a theoretical study with a case example on the relationships among wetland salinity, farmland drainage processes and wetland inflow and outflow management. The proposed mathematical models were tested with a case study in a semi-arid region of China, to display salinity changes with time in the drainage disposal wetlands. Practical salinity management options for sustainability of the system were recommended.

## 2. Materials and methods

Based on the general farmland drainage practice in irrigated agricultural areas and assuming that drainage water is temporarily stored in low lying wetlands other than immediately discharged out of the area, mathematical models are derived to represent the theoretical relationships for salt and water balance in such a system. A case study in Lubotan, Shaanxi, China is used to display the model application. As a general solution, the term ‘wetland’ used here refers to different types of entities that work together as a drainage water disposal site, including the conventional wetlands and other hydrologically connected water bodies that display wetland characteristics, such as open drainage ditches. The proposed models represent the general situation of wetlands serving as drainage outlet in irrigated agricultural areas. In the case study example, however, wetlands were drainage ditches that may be viewed as a single wetland entity; these ditches retain their original functions of being the passage way for drainage discharge. Fig. 1 presents the relationship of the salt and water balance within the ‘farmland drainage–wetland disposal’ system analyzed in this paper, and the drainage water discharged from the farmland may be partially or entirely lost in the ditches through the evapotranspiration process.

### *2.1. Mathematical models for salt and water balance in the ‘farmland drainage–wetland disposal’ system*

The water supplies of wetlands in irrigated areas are mainly from farmland drainage and some local precipitation. Drainage contains the most salt and it is the direct cause of salt accumulation in wetlands. Before examining the salt and water balance in the ‘farmland drainage–wetland disposal’ system, the agricultural drainage process is firstly looked at.

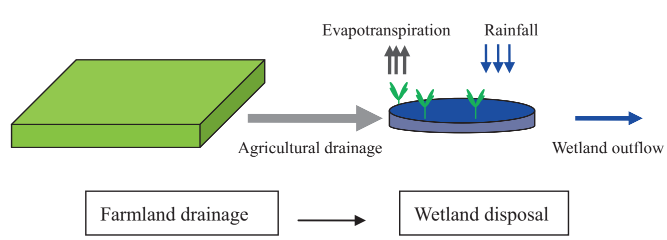


**Fig. 1.** Sketch of the salt and water balance in farmland drainage and wetland disposal system.

#### 2.1.1. Salt leaching requirements of farmlands

For irrigated farmlands, irrigation water requirement includes crop water requirement and salt leaching requirement. Leaching fraction ($LF$) can be expressed as the depth ratio of subsurface drainage over irrigation:

$$LF = \frac{H_d}{H_{irr}} \tag{1}$$

where $H_d$ is the annual drainage depth, $H_{irr}$ is the annual irrigation depth which can be further written as:

$$H_{irr} = \frac{ET_c - R_{eff}}{1 - LF} \tag{2}$$

where $ET_c$ is the annual crop water requirement or evapotranspiration, $R_{eff}$ is the annual effective rainfall.

Assuming that the salt balance in the drained fields has reached equilibrium, i.e., the rate of salt leaching out of the fields is equal to the rate of salt influx, then the salinity of the drainage water is inversely proportional to $LF$, expressed as:

$$EC_d = \frac{EC_{irr}}{LF} \tag{3}$$

where $EC_d$ and $EC_{irr}$ are salinity (expressed as electrical conductivity) of the drainage and irrigation water, respectively.

For a region with a certain irrigation water quality, the required minimum $LF$ can also be calculated with the following equation (Ayers and Westcot, 1985):

$$LF = \frac{EC_{irr}}{5EC_e - EC_{irr}} \tag{4}$$

where $EC_e$ is electrical conductivity of soil saturation extract. Irrigation water salinity in a region usually remains stable; $LF$ is thus a function of soil salinity only. Once the threshold level of soil water salinity ($EC_d{}^*$) for a concerned crop is determined, the minimum leaching requirement or the critical value of $LF$ ($LF^*$) can be calculated from Eq. (3). The minimum annual drainage depth ($H_d{}^*$) can now be calculated:

$$H_d{}^* = \frac{(ET_c - R_{eff})LF^*}{1 - LF^*} \tag{5}$$

Under minimum drainage condition, drainage water salinity can be assumed equal to the soil water salinity.

#### 2.1.2. Water balance in the 'farmland drainage–wetland disposal' system

Once the volume and salinity of agricultural drainage water are estimated, salt dynamics in the 'farmland drainage–wetland disposal' system, as sketched in Fig. 1, are investigated. The variable, $\alpha$ is defined as the ratio of wetland area ($A_{wet}$) over farmland area ($A_{ag}$):

$$\alpha = \frac{A_{wet}}{A_{ag}} \tag{6}$$

A wetland outflow ratio, $\beta$ is introduced and expressed mathematically as:

$$\beta = \frac{W_{out}}{W_{in}} \tag{7}$$

where $W_{out}$ is the annual volume of outflow leaving the wetland and $W_{in}$ is the annual volume of wetland inflow. $W_{in}$ can be calculated as the product of farmland area ($A_{ag}$) and drainage depth ($H_d$). Hydrologically, the 'farmland drainage–wetland disposal' system may either be an open or a closed system. When $\beta = 0$, the 'farmland drainage–wetland disposal' system is a closed unit, and the wetland is essentially an evaporation pond for the drainage water. When $\beta = 1$, the wetland is a passage way for the drainage water, and salt and water retention in the wetland is negligible. When $\beta$ is between 0 and 1, part of the drainage water (inflow) is consumed in the wetland through the evaporation process, and salt will gradually build up before reaching an equilibrium state. Denoting annual $ET$ of the wetland as $ET_{wet}$ and rainfall as $R$, the water balance of the 'farmland drainage and wetland disposal' system, as depicted in Fig. 1, can be expressed as:

$$A_{ag}H_D + A_{wet}R = \beta A_{ag}H_d + A_{wet}ET_{wet} \tag{8}$$

If no buildup of water level in wetlands is desired, the minimum area ratio of farmland ($A_{ag}$) over the wetland ($A_{wet}$) required to consume drainage water can be further written as

$$\alpha = \frac{A_{wet}}{A_{ag}} = \frac{(1-\beta)H_d}{ET_{wet} - R} \tag{9}$$

when $\beta = 0$, drainage is consumed entirely in a closed system and the maximum area ratio becomes

$$\alpha = \frac{H_d}{ET_{wet} - R} \tag{10}$$

#### 2.1.3. Salt balance in wetlands under equilibrium state

As conservative substances, salts entering the wetland have 4 passages: (1) storage in the wetland water body; (2) storage in the wetland soils; (3) leaving the system with outflow discharge; and (4) leaving the system through plant uptake and harvest. In view of the salinity changing process, from the establishment of a 'farmland drainage–wetland disposal' system to the salinity stabilization, salt storages in the water body and the soil are temporary. Only before salinity of the system reaches equilibrium, there are spaces for salt concentration growth in the water body ($C_w$) and the soil ($C_s$) of the wetland. Outflow discharge and plant uptake will remove salts from the wetland system permanently. Defining an annual plant uptake of salt per unit area, $W_p$, salt balance in the wetland water in equilibrium state ($C_w = C_w{}^*$) can be written as:

$$C_dH_dA_{ag} = \beta H_dA_{ag}C_w{}^* + A_{wet}W_p \tag{11}$$

The left hand side of Eq. (11) represents the annual salt input into the wetland with the drainage water, and the right hand side represents the annual salt removal through outflow discharge ($\beta H_dA_{ag}C_w{}^*$) and plant uptake ($A_{wet}W_p$); Salt concentration of the wetland water body can be calculated as:

$$C_w{}^* = \frac{C_dH_dA_{ag} - A_{wet}W_p}{\beta H_dA_{ag}} \tag{12}$$

Eq. (12) implies that when the total amount of salts entering the wetland is a constant, salt concentration (or salinity) at equilibrium is affected by plant uptake and the drainage depth. The numerator ($C_dH_dA_{ag} - A_{wet}W_p$) represents the annual net salt input to wetlands, thus the wetland water salinity ($C_w{}^*$) is inversely proportional to the outflow ratio, $\beta$. Plant uptake of salts is usually smaller than the salt input to the wetlands, i.e., ($C_dH_dA_{ag} - A_{wet}W_p$) is greater than zero. If the outflow discharge is negligible, i.e., $\beta \to 0$, salt concentration of the wetlands will rise up to an infinite level. Therefore, outflow discharge from the wetlands is necessary to maintain the salinity below a certain level.

#### 2.1.4. Salt balance in wetlands prior to equilibrium state

When there is no substantial variation in annual water level in the wetland, the salt balance of the water body and the soil are given by, respectively:

$$C_dH_dA_{ag} = \beta H_dA_{ag}C_w + A_{wet}W_p + k_sA_{wet}(C_w - C_s) + A_{wet}H_w\frac{dC_w}{dt} \tag{13}$$

$$A_{wet}H_s\frac{dC_s}{dt} = k_sA_{wet}(C_w - C_s) \tag{14}$$

where $k_s$ is the flux of salt exchange between water body and soil; $H_w$ is the average annual water depth in wetland; $H_s$ is the water equivalent depth for the soil in wetlands, which equals to the product of the salt retention depth ($H_s'$) and porosity of the soil ($\Theta$); and $t$ is the time in years.

Rearranging Eqs. (13) and (14) results in:

$$A_{wet}H_w\frac{dC_w}{dt}+K_sA_{wet}(C_w-C_s)+\beta H_dA_{ag}C_w=C_dH_dA_{ag}-A_{wet}W_p \quad (15)$$

$$C_w=\frac{H_s}{k_s}\frac{dC_s}{dt}+C_s \quad (16)$$

Let $C_dH_dA_{ag}-A_{wet}W_p=M$, and substituting Eq. (16) in (15), the following equation is obtained:

$$A_{wet}H_w\frac{H_s}{k_s}\frac{d^2C_s}{dt^2}+\left(A_{wet}H_w+A_{wet}H_s+\frac{\beta H_dA_{ag}H_s}{k_s}\right)\frac{dC_s}{dt}+\beta H_dA_{ag}C_s=M \quad (17)$$

Let $Q=\dfrac{k_s}{H_s}+\dfrac{k_s}{H_w}+\dfrac{\beta H_d}{\alpha H_w}$, $R=\dfrac{\beta H_dk_s}{\alpha H_wH_s}$, and $S=\dfrac{Mk_s}{A_{wet}H_wH_s}$

Then, an inhomogeneous second order ordinary differential equation is obtained to describe soil salinity:

$$\frac{dC_s{}^2}{d^2t}+Q\frac{dC_s}{dt}+RC_s=S \quad (18)$$

The solution of Eq. (18) includes a general solution and a particular solution. The general solution is

$$C_s=X_1e^{r_1t}+X_2e^{r_2t} \quad (19)$$

where $X_1$ and $X_2$ are constants determined by the boundary and initial conditions; $r_1$ and $r_2$ are solutions to the characteristic equation $r^2+Qr+R=0$, which has real solutions of $r_{1,2}=(-Q\pm\sqrt{Q^2-4R})/2$ under two conditions, i.e., $\sqrt{Q^2-4R}>0$ and $\sqrt{Q^2-4R}=0$. When $\sqrt{Q^2-4R}>0$, the solutions are $r_1=(-Q+\sqrt{Q^2-4R})/2$ and $r_2=(-Q-\sqrt{Q^2-4R})/2$.

A particular solution of Eq. (18) is

$$C_s=\frac{S}{R} \quad (20)$$

Substituting the values of $S$ and $R$ in Eq. (20), the particular solution gives the salt concentration of wetland soil and water under equilibrium condition, i.e., $C_s=C_w{}^*$.

Combining the general and the particular solutions gives the salinity of the wetlands soil:

$$C_s=X_1e^{r_1t}+X_2e^{r_2t}+C_w{}^* \quad (21)$$

Substituting Eq. (21) in (16) gives the salinity of the wetland water body:

$$C_w=X_1\left(1+\frac{H_s}{K_s}r_1\right)e^{r_1t}+X_2\left(1+\frac{H_s}{K_s}r_2\right)e^{r_2t}+C_w{}^* \quad (22)$$

Because the coefficients of the homogeneous equation are all positive, the values of $r_1$ and $r_2$ are all negative. When values of the constants $X_1$ and $X_2$ are determined, the salinity variation from the initial to the equilibrium state can be calculated.

### 2.2. Case study site description and data collection

The case study site is a reclaimed salinized land area located in Shaanxi, China (Fig. 2). It belongs to the warm temperate semi-arid climatic zone with an annual mean temperature of 13.4 °C, an annual mean precipitation of 473 mm and an evaporation of 1200 mm. The area was part of the ancient Sanmen Lake in China and receded into wetland (Lubotan) about 400 years ago. Some farming activities have been concentrated on the higher grounds of the area in recent decades. A few drainage ditches were excavated for crop production in the 1960s but salinization of the site remained a problem. Besides natural precipitation, surface runoff from two upstream irrigation districts discharge into the Lubotan area at the end of each irrigation season for its low lying position. As arable land is becoming increasingly limited due to the local economic development, an intensive land reclamation project was carried out in 1999 by means of land leveling and drainage ditch construction; many potholes were filled and water surface is now limited to the man made drainage ditches that continues to provide the habitat for some wild waterfowls. Fig. 2 displays the newly constructed strip fields and the matching drainage system. Drainage water from the irrigated farmland was initially planned to be discharged into a nearby river through a main drainage ditch, but construction of the main ditch was disrupted for both environmental and economic reasons, and the main ditch ended in a small depression as shown in Fig. 2. The constructed field drainage ditches at Lubotan are 100 m apart and 2.5 m deep. These field ditches are connected to the branch and the main ditches as shown in Fig. 2. In addition to the subsurface drainage from the local area, the main ditches also receive a significant amount of freshwater discharge from two upstream irrigation districts as mentioned above. As a result of these water supplies, the drainage ditches, especially the main ditches, are ponded for a relatively long time of the year and flourished with wetland plants, mostly reeds (*P. australis*), as shown in Fig. 3.

After the land reclamation project, sporadic salinization is still visible in some fields, but most crops including cotton and wheat are growing nearly normal. For lack of a drainage outlet in the reclamation area, there is a concern that salinity will build up with time to threaten crop production. Salinity observation in the wetland ditches, however, showed no significant increase in recent years. One speculation is that the upstream discharge of freshwater is beneficial for salinity control at Lubotan by flushing out salts accumulated in the drainage ditches. In order to study the salinity dynamics in the 'farmland drainage–wetland disposal' system at Lubotan, salinity changes are monitored in the crop fields and the wetland ditches since early 2009. In a selected corn field and a cotton field, clusters of three groundwater monitoring wells were installed separately in the middle, and at quarter distances from the two parallel drainage ditches. Each cluster of wells was drilled to depths of 1–3 m. Staff gages were installed in ditches for water level measurement. Water samples were collected bi-weekly from the observation wells in the crop fields and designated locations in ditches for salinity determination in the laboratory. Water levels in the wells and ditches were recorded simultaneously. Water quality sampling and water level measurement locations can be indentified in Fig. 2.

## 3. Results and discussions

### 3.1. Agricultural drainage and wetland distribution in Lubotan

#### 3.1.1. Threshold drainage depth calculation

According to local crop water requirement studies (SDWOR, 1991), seasonal evapotranspiration is 711 mm for cotton and 479 mm for corn; the effective rainfall is 414 mm for cotton and 289 mm for corn in Lubotan. Irrigation water of the area is diverted from the Yellow River with a relatively constant salinity of 0.5 g $L^{-1}$. Taking the threshold salinity of the soil saturation extract for achieving 100% crop yield as 3.26 g $L^{-1}$ for cotton, and 0.7 g $L^{-1}$ for corn (Ayers and Westcot, 1985), the critical leaching factor calculated with Eq. (4) was 3.2% for cotton and 16.6% for corn, and their corresponding threshold drainage depths calculated with Eq. (5) were 23.2 and 95.1 mm for cot-

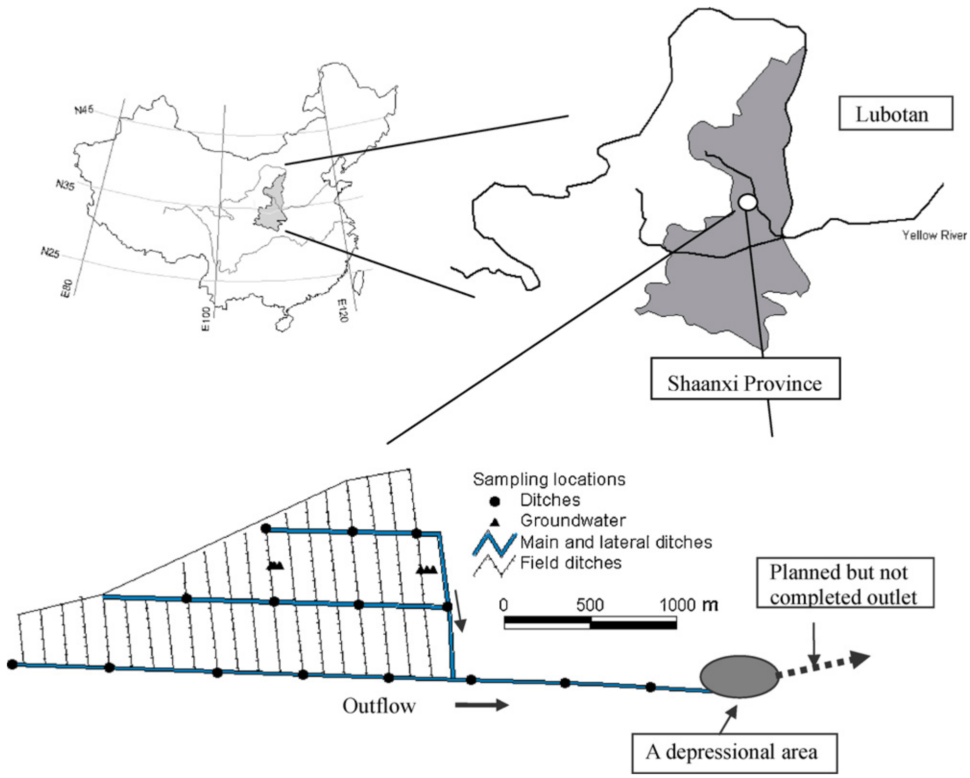


**Fig. 2.** Location of the study site and schematic layout of the drainage system at Lubotan, Shaanxi, China. Ditch sample locations are denoted by solid circles and groundwater sample location by solid triangles.

ton and corn, respectively. Based on the drainage requirements and a cropping pattern of 60% cotton and 40% corn, the area weighted average drainage depth was 52.0 mm and the average salinity 10.7 g $L^{-1}$.

### 3.1.2. *Groundwater salinity and current drainage depth*

The observed groundwater salinity near the drainage ditches was 6.38 and 4.40 g $L^{-1}$ in the cotton and corn field, respectively; the calculated threshold drainage water salinity was 15.82 g $L^{-1}$ for cotton and 3.02 g $L^{-1}$ for corn. Based on the cropping pattern of 60% cotton and 40% corn, the calculated area weighted average drainage depth was 60.7 mm and the salinity was 5.60 g $L^{-1}$ under current practice. These results showed that the current drainage volume at Lubotan is slightly higher than the threshold level of 52 mm based on the proposed theoretical model, and the current salinity of the drainage water is much lower than the threshold level of 10.7 g $L^{-1}$ as presented above.

### 3.1.3. *Wetland to farmland area ratio*

The study area is divided into strip fields of 4 ha in rectangles of 100 m × 400 m. As shown in Fig. 3, the fields are surrounded by drainage ditches that are considered as wetlands. The total area of farmland is 160.0 ha, and the wetland ditches cover 14.61 ha. The area ratio of ditches over farmland is 9.1%. Based on the agricultural land area and drainage water depth obtained above, the calculated annual drainage volume is 97,059 $m^3$, and the annual salt input into the wetland is 542,179 kg. The drainage inflow is equivalent to a water depth of 664.4 mm over the ditch area. Fig. 4 presents the relationships between the ditch outflow ratio ($\beta$) and the required minimum area ratio predicted by Eq. (9), as well as the equilibrium salinity of the wetland as a function of the outflow ratio predicted by Eq. (12). For the current wetland to farmland area ratio of 9.1% at Lubotan, the outflow ratio should be 58.2% or higher to maintain the equilibrium state of the water balance. Such a high outflow ratio indicates that the 'farmland drainage–wetland disposal' system cannot be a hydrologically closed system; more than half of

**Fig. 3.** Drainage ditches flourished with wetland plants at Lubotan.

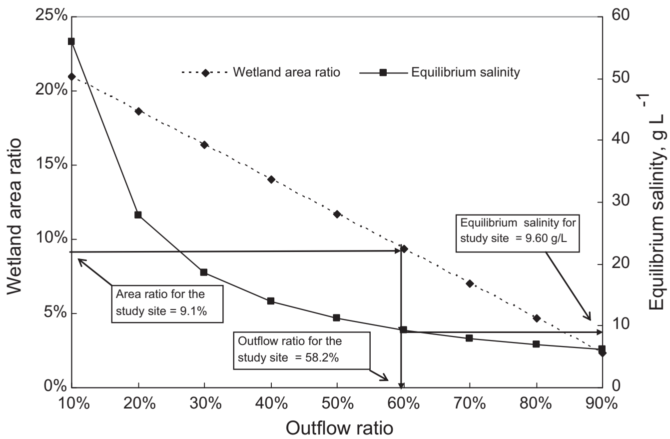


**Fig. 4.** The relationships among wetland outflow ratio, minimum wetland to farmland area ratio and equilibrium salinity.

**Table 1**
Parameter values used for ditch salinity predictions in the case example.

| Notation | Description | Value used | Units |
|---|---|---|---|
| $A_{ag}$ | Farmland area | 1,704,167 | $m^2$ |
| $A_w$ | Ditch area | 225,997 | $m^2$ |
| $H_w$ | Average water depth in the ditch | 0.3 | m |
| $ET_w$ | ET in the ditch | 0.9 | $m\,yr^{-1}$ |
| $R$ | Rainfall | 0.54 | $m\,yr^{-1}$ |
| $H_s$ | Water equivalent depth of the soil | 0.15 | m |
| $H_s'$ | Effective depth of the soil | 0.3 | m |
| $\Theta$ | Porosity | 0.5 | - |
| $k_s$ | Flux of salt exchange between wetland water and soil[a] | 0.365 | $m\,yr^{-1}$ |
| $W_p$ | Plant uptake rate over unit area[b] | $0.574 \times 10^{-3}$ | $kg\,m^{-2}\,yr^{-1}$ |

[a] From Thomann and Muller (1987).
[b] Based on Li et al. (2008) for a 50% coverage and 20% harvest ratio.

the agricultural drainage water has to be removed from the system each year.

### 3.2. A simple verification of the analytical model based on salinity monitoring

Because the proposed analytical model was derived on an annual average basis, it can be appropriately used for long-term predictions of salt dynamics in wetlands receiving agricultural drainage. Unfortunately long-term monitoring data are not available from the current study site or other sources. The wetland disposal system in the study area has been in operation since 2000, but its salinity growth trend is irregular as a result of the yearly random release of fresh water from the two upstream irrigation districts, as shown in Fig. 5. Before each recharge event, salinity of the ditch system was observed to increase with time as a result of the evaporation effect, but the freshwater inflow quickly lowered the salinity in the ditches as indicated by the fluctuations of salinity values plotted in Fig. 5. The random nature of the inflow events allows us to observe the consistent trend of salinity increase only during certain time periods. As marked in Fig. 5, the longest period without observed recharge events was from November 5, 2009 to June 24, 2010, and this period was chosen for verifying the proposed analytical model for wetland salinity changes. In late fall of 2009, a certain volume of freshwater, discharged from an upstream irrigation district, entered the drainage ditches at Lubotan and reduced ditch salinity from 4.81 to 2.18 $g\,L^{-1}$, while the salinity of the soil at ditch bottom sampled down to 50 cm was reduced to 2.24 $g\,L^{-1}$. Thenceforth, a gradual increase of salinity in the wetland ditch system was observed until June 24, 2010 when another inflow event occurred. So the monitoring data between December 16, 2009 and June 24, 2010 were used to test the model; and the salinity measurements on December 16, 2009 were used as the initial values. Based on the data listed in Table 1, the salinity increasing process was calculated with Eqs. (21) and (22) and plotted in Fig. 6 together with the measured data. The calculated salinity values matched the measurements very well on the two sampling events: one on May 23, 2010 (lapsing time = 0.43 year) when the measured ditch water salinity was 4.38 $g\,L^{-1}$ and the predicted value was 4.35 $g\,L^{-1}$; and the other one on June 21, 2010 (lapsing time = 0.51 year) when the measured ditch water salinity was 4.62 $g\,L^{-1}$ and the predicted value was 4.52 $g\,L^{-1}$. The fresh water recharge occurred somewhere in the middle of the western boundary at Lubotan, while the salinity

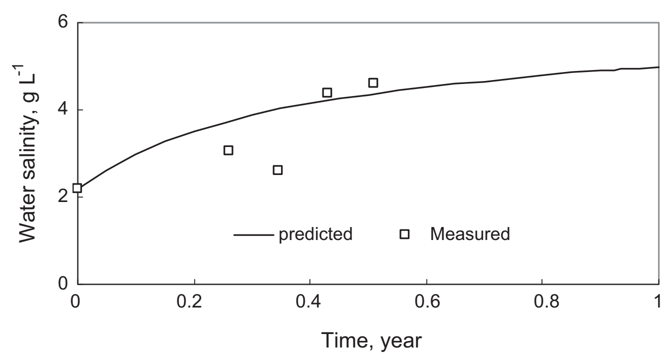


**Fig. 6.** Predicted and observed salinity change in wetland ditches after a recharge event in December 2009 at Lubotan.

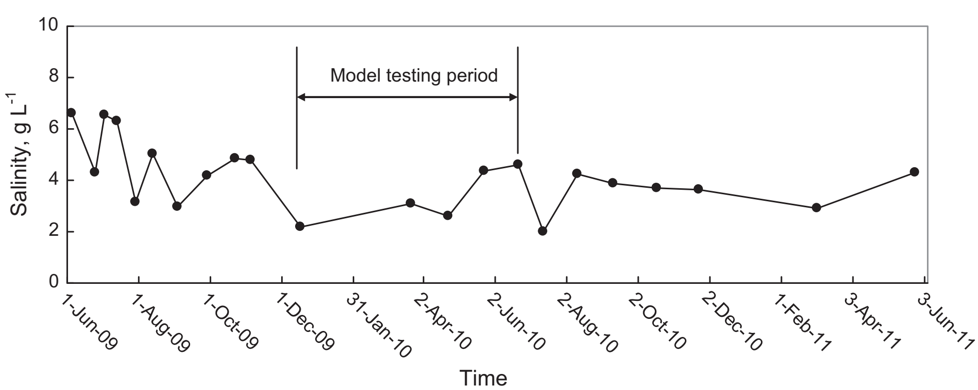


**Fig. 5.** Measured average salinity change in wetland ditches at Lubotan.

measurements were taken from different locations in the drainage ditches as indicated in Fig. 1. Therefore, some inconsistencies in the monitoring data were observed as mixing of fresh water with salty water took place slowly in the wetland system. The measurement on June 21, 2010 reflected the overall wetland condition better. As listed in Table 1, the values of wetland water and soil depth used for calculation were taken from field observations, and others were taken from literature reports. In addition to our monitoring study, we learned from interviewing local people that since year 2000 the ditches have been ponded during most time of the year by shallow water and there has been no obvious water level building up. Such observations imply that the outflow ratio of the ditch wetland system is close to the value computed by Eq. (9) as illustrated in Fig. 4. The reason is simple: the ditches would dry up during some periods of the year if the outflow ratio was much greater than the predicted value; and vice versa, water level would gradually build up in the ditches if the outflow ratio was much lower than the predicted outflow ratio.

In Table 1 a salt removal rate of $0.574 \times 10^{-3}$ kg m$^{-2}$ yr$^{-1}$ is listed through plant uptake by harvesting wetland plants. This value was calculated as the product of the annual salt removal rate of 5.74 g/m$^2$ reported by Li et al. (2008), a vegetation coverage of 50% and harvesting ratio of 20% based on field observations. The calculated annual salt removal by harvesting wetland plants was 83.9 kg, accounting for 0.2% of the annual salt input from agricultural drainage. Hence the salt removal by wetland plants can be considered negligible in Lubotan.

### 3.3. Wetland salinity dynamics

#### 3.3.1. Wetland salinity at the equilibrium state

As can be seen from Eq. (12), salinity of the wetland at the equilibrium state is related to the farmland drainage characteristics, plant uptake of salt and wetland outflow ratio. Based on available information of the case study area and the parameters listed in Table 2, the ditch water salinity at equilibrium state was calculated using Eq. (12), and plotted in Fig. 4. When the outflow ratio is 10%, the calculated equilibrium salinity of the ditch system was as high as 55.84 g L$^{-1}$; when the outflow ratio increases to 30%, the calculated equilibrium salinity was reduced to 18.64 g L$^{-1}$; when the outflow ratio increases to 50%, the calculated equilibrium salinity was reduced to 11.17 g L$^{-1}$. For such wetland system, if the desired outflow discharge ratio cannot be reached, fresh water supply has to be provided to adjust the salinity level.

#### 3.3.2. Salinity changes in the wetland system prior to the equilibrium state

Prior to reaching the equilibrium state, salt concentration in the wetland will rise gradually with drainage inflow. Eqs. (21) and (22) present how the salinity in the wetland water body and soil will change with the other variables. For the case study area, using the measured salinity values of December 2009 as initial condition, salinity variations in 30 years were calculated and presented in Fig. 7, while the salinity changes for time increments of 5 years

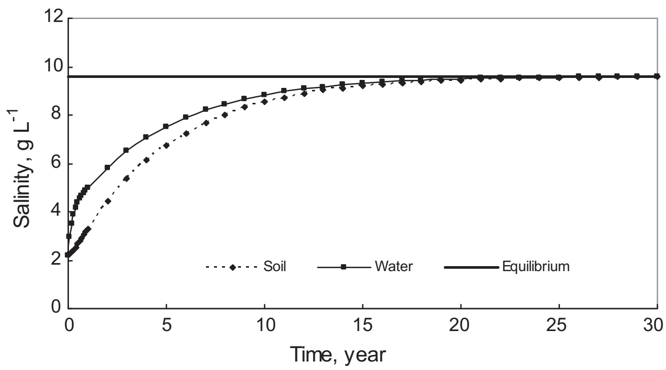


**Fig. 7.** Predicted temporal variation of salinity in the water body and soil of the wetland for a wetland area ratio of 9.1% and an outflow ratio of 58.2%.

were listed in Table 2. The initial salinity was 2.18 g L$^{-1}$ for the ditch water and 2.24 g L$^{-1}$ for the soil, and are both 23% of the equilibrium salinity (10.54 g L$^{-1}$). Fig. 7 shows that the rate of salinity increase slowed down with the time elapsed. The salinity for water body and soil both started to grow from 23% of the equilibrium levels but, thereafter, the salinity of the water body was consistently slightly higher than that of the soil. The greatest increase of the wetland ditch salinity was observed in the first 5 years, and ranged from 2.18 to 7.52 g L$^{-1}$ in the water body and from 2.24 to 6.75 g L$^{-1}$ in the soil, accounting for 78% and 70% of the equilibrium salinity in the wetland, respectively. After 10 years, the predicted salinity values were 8.83 g L$^{-1}$ in the water body and 8.54 g L$^{-1}$ in the soil, accounting for 92% and 89% of the equilibrium salinity. By the end of year 15, the predicted salinity levels reached 9.31 g L$^{-1}$ in the water body and 9.21 g L$^{-1}$ in the soil, approaching the equilibrium salinity of 9.60 g L$^{-1}$.

Table 3 lists the predicted mean annual increase of the ditch salinity in 5 years intervals over a period of 30 years. The rate of salinity increase slowed down with time: it dropped from 1.07 and 0.90 g L$^{-1}$ yr$^{-1}$ in the water and the soil, respectively, in the first 5 years to 0.26 and 0.36 g L$^{-1}$ yr$^{-1}$ in the second 5 years. In the third 5-year period (10–15), the rate of salinity increase dropped to 0.10 and 0.03 g L$^{-1}$ yr$^{-1}$ in the water body and the soil, respectively, accounting for only 9% and 15% of the annual increments during the first 5 years.

### 3.4. Management options for wetland salinity control

Several options are possible to keep wetland salinity from breaching a critical level. The leaching fraction of the cropland could be increased to produce more drainage water of lower salinity to the wetland while maintaining a minimum outflow ratio from the wetland. This option, however, is not practical for areas like Lubotan considering the limited space of wetland and the irrigation conservation requirement.

According to the relationships presented in Fig. 4, the option of recharging or flushing the wetlands with fresh water before

**Table 2**
Predicted wetland salinity change with operation years.

| Wetlands | System operation years | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 | 25 | 30 |
| Water | | | | | | | |
| Year end salinity (g L$^{-1}$) | 2.18 | 7.52 | 8.83 | 9.31 | 9.49 | 9.56 | 9.58 |
| % of the equilibrium salinity | 23 | 78 | 92 | 97 | 99 | 100 | 100 |
| Soil | | | | | | | |
| Year end salinity (g L$^{-1}$) | 2.24 | 6.75 | 8.54 | 9.21 | 9.45 | 9.54 | 9.58 |
| % of the equilibrium salinity | 23 | 70 | 89 | 96 | 98 | 99 | 100 |

**Table 3**
Predicted average annual increase of wetland salinity during different operation periods.

| Wetland | Average annual increase of wetland salinity (g L$^{-1}$ yr$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | 1st–5th year | 5–10th year | 10–15th year | 15–20th year | 20–25th year | 25–30th year |
| Water body | 1.07 | 0.26 | 0.10 | 0.04 | 0.01 | 0.00 |
| Soil | 0.90 | 0.36 | 0.13 | 0.05 | 0.02 | 0.01 |

**Table 4**
Predicted time for ditch salinity reaching threshold levels and water requirement for dilution recharge at Lubotan reclamation area.

| Threshold salinity (g L$^{-1}$) | Predicted time to reach threshold level (year) | Recharge water required | |
|---|---|---|---|
| | | Depth (m) | Volume[a] (m$^3$) |
| 5 | 1 | 0.75 | 109,564 |
| 7 | 4 | 1.29 | 187,824 |
| 9 | 12 | 1.82 | 226,083 |

[a] Ditch area = 146,085 m$^2$.

the wetland salinity reaches a critical level can now be examined. Because it takes years for the wetland to reach the critical salinity level, the recharge can be carried out during the wet seasons or years. For water deficient regions the recharge can be scheduled at the end of the growing season when the irrigation requirement is low and ample supply of fresh water is available.

Because the threshold salinity level of wetland is dependent on the ecological functions of the system, hypothetical values of three threshold salinity levels (5, 7 and 9 g L$^{-1}$) are assumed as examples to predict the time required to "restore" the wetland and the amount of fresh water needed for the recharge process. Using the measured ditch salinity of 2.18 g L$^{-1}$ in the water body and 2.24 g L$^{-1}$ in the soil in 2009 at Lubotan as the initial conditions, time and water requirement for wetland recharge are calculated, as listed in Table 4. The predicted results show that for the case study site, the time required to reach a salinity level of 5 g L$^{-1}$ is nearly one year, to reach a salinity level of 7 g L$^{-1}$ is about 4 years, and to reach a salinity level of 9 g L$^{-1}$ is more than 12 years. The salinity level of the ditch system is expected to increase at a relatively slow rate before reaching the equilibrium state.

Assuming that the recharge water has the same salinity of 0.5 g L$^{-1}$as the irrigation water, Table 4 shows that to lower ditch salinity back to its initial level by fresh water recharge, the calculated water requirement was 0.75, 1.29 and 1.82 m in order to maintain the threshold salinity below 5, 7 and 9 g L$^{-1}$, respectively. Therefore, a management decision is to choose a proper threshold salinity level that is both ecologically sound and economically feasible.

The recharging water need be drained from the wetlands after it is well mixed with the salty water of the wetlands, otherwise the salinity level of the wetland will increase rapidly due to the evaporation process, and the goal of 'refreshing or restarting the system' cannot be achieved. Lamontagne et al. (2006) observed such a rapid recovery of salinity in Australia due to a high evaporation rate. Because the outflow ratio for Lubotan is close to 58%, it is expected that the water level in the ditches will drop to the average depth in a relative short period. This is consistent with the observations at Lubotan where the water level in the ditches quickly lowered after being filled up by the freshwater recharge released from the upstream irrigation districts. The high water level in the ditches moved the salty water down to a low lying depression downstream as shown in Fig. 2.

### 3.5. Salt buffering capacity of the wetland soil

Theoretically, wetland soil has a buffering capacity to salinity change in the water body; but the effective depth for salt retention of wetland soil is limited, resulting in a soil salinity change in conformity with the water body. In the case study calculations, soil down to 0.3 m beneath the ditch bottom is used for calculating salt exchange between ditch soil and water based on site observations; this soil depth was converted to water equivalent depth by multiplying an effective porosity of 0.5. The calculated water equivalent depth of the ditch soil with exchange capability was only 0.15 m, indicating that the influence of wetland soil on salinity variation is very limited. As Fig. 7 shows, the predicted salinity levels in ditch soil and water body have no significant difference. In order to examine the effect of soil depth on salinity changes in wetland, soil depths of 0.5 and 0.7 m are further examined. For ditch soil depths of 0.3, 0.5 and 0.7 m, the calculated water equivalent depths are 0.15, 0.25 and 0.35 m, respectively, accounting for 50%, 83% and 117% of the water depth in ditch (0.3 m). Fig. 8 shows that

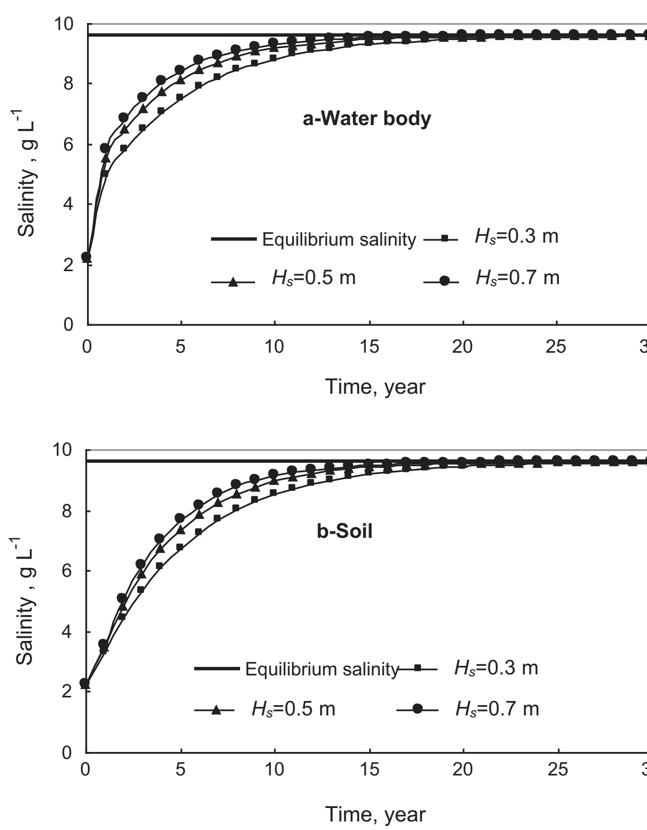


**Fig. 8.** Predicted salinity change with time in (a) water body and (b) soil of wetland ditches as affected by bottom soil depth ($H_s$) for an outflow ratio of 58.2%.

although deeper soil stored more salts as the soil salinity displayed more rapid increase initially, the predicted salinity levels in water body and soil had no significant difference either in magnitude or trend. The difference in salinity increase was the greatest in the first 5 years of the system operation, when soil depth increased from 0.3 m to 0.5 m, the salinity increased by 0.6 g $L^{-1}$; when soil depth increased from 0.3 m to 0.7 m, the salinity increased by 1 g $L^{-1}$. At the end of the 10th year, the differences were reduced to about 0.3 and 0.6 g $L^{-1}$ for soil depths of 0.5 and 0.7 m, respectively. These differences, however, are not significant when compared with the absolute salinity values. So, the wetland soil has no significant effect on the salt dynamics of the system, i.e., the salt buffering capacity of the wetland soil is very limited.

## 4. Conclusion

For wetlands receiving salt-laden drainage water in arid or semi-arid irrigation areas, salinity may eventually build up to critical levels that are detrimental to the ecological service of the wetland system. Theoretical analysis with a case example presented in this paper showed that with proper salinity management practices, wetlands that receive drainage discharge in semi-arid regions can be sustained to the maximum benefit of the agricultural system and the environment. The results showed that wetland salinity management can be realized by recharging the wetlands with fresh water at regular time intervals. Salt and water balance analysis in this study considered agricultural drainage as the sole inflow to wetlands, while in some situations various types of inflow may exist, which will either have a positive or negative effect on wetland salinity. The quantitative conclusions drawn from the case study presented in this paper may be applicable to similar climatic conditions and the methodology proposed in this study can be extended for wider applications.

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