IAEA-TECDOC-1811

IAEA TECDOC SERIES

IAEA-TECDOC-1811

# Guidelines for Developing Wetlands in Agricultural Catchments

Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

IAEA
International Atomic Energy Agency

# GUIDELINES FOR DEVELOPING WETLANDS IN AGRICULTURAL CATCHMENTS

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA-TECDOC-1811

# GUIDELINES FOR DEVELOPING WETLANDS IN AGRICULTURAL CATCHMENTS

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

For further information on this publication, please contact:

Soil and Water Management and Crop Nutrition Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org


Printed by the IAEA in Austria
March 2017

**IAEA Library Cataloguing in Publication Data**

Names: International Atomic Energy Agency.
Title: Guidelines for developing wetlands in agricultural catchments / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2017. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1811 | Includes bibliographical references.
Identifiers: IAEAL 17-01079 | ISBN 978–92–0–100917–3 (paperback : alk. paper)
Subjects: LCSH: Wetland hydrology. | Watershed hydrology. | Constructed wetlands.

# FOREWORD

The Food and Agricultural Organization of the United Nations and the IAEA, through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture (Joint Division), support Member States to implement improved and sustainable agricultural and water management practices for food security and to ensure that agricultural production systems are resilient to the impacts of climate change, that greenhouse gas emissions are reduced, and that the impacts of agriculture on the quality of land and water resources are minimized.

In many regions in the world, wetlands play a significant role in water resource management. In addition to providing water for agriculture, they can improve water quality, reduce flood risk and downstream siltation, and enhance groundwater recharge. They also help to improve soil moisture and to enhance soil fertility and quality.

Although water storage systems have been developed and studied, their use in agricultural landscapes have not reached their full potential. A greater understanding of the complexities of these systems for improving water quality and enhancing agricultural water use efficiency would help Member States to address wetland management challenges. More comprehensive knowledge of the relationship between upstream land use and the functions of wetlands in agricultural landscapes is necessary. Therefore, guidelines for developing and monitoring wetlands are important for their effective use in water harvesting, agriculture and the environment.

The Soil and Water Management and Crop Nutrition Subprogramme of the Joint Division initiated an international coordinated research project (CRP) to collect information on water sources and sinks in wetlands, water and nutrient budgets, and the internal dynamics of water, sediment, plants and nutrients. The CRP on Management and Areas-wide Evaluation of Water Conservation Zones in Agricultural Catchments for Biomass Production, Water Quality and Food Security was implemented between 2008 and 2013, and the findings were published in IAEA-TECDOC-1784. Information collected from the CRP was used to develop this publication.

This publication provides information to researchers working in the area of land and water management, natural resource managers, policy makers and farmers. It describes protocols to be followed for wetland development, from planning to implementation, monitoring and evaluation. Isotopic and nuclear techniques were used to assess water dynamics and to identify the ideal locations for developing wetland development.

The IAEA wishes to thank all the CRP participants for their valuable contributions to the project and the development of the guidelines. The IAEA officer responsible for this publication was K. Sakadevan of the Joint Division FAO/IAEA of Nuclear Techniques in Food and Agriculture.

**CONTENTS**

# 1. INTRODUCTION

## 1.1. BACKGROUND

A majority of agricultural production systems in developing countries usually depend on rainfall due to insufficient irrigation and water resource infrastructure. However, erratic rainfall makes agricultural production unstable in many parts of dry areas around the world [1]. Water stress is rapidly increasing in many areas across Asia–Pacific, Africa, Latin–America, North America and Europe due to expansion of agriculture to dry areas. The large scale development of dams and reservoirs to collect and store water for irrigation in developing countries has become difficult due to lack of financial resources to build and operate these systems.

Economically feasible technologies and practices for the harvesting and efficient use of water in developing countries are thus required for sustainable intensification of crop production and improve overall agricultural water management that could result in improved water–quality and water use efficiency. Harvesting rainwater in these dry areas and using them effectively for crop production during an extended dry period can stabilise and increase crop yields and overall agricultural productivity.

On–farm wetlands are important components of water resource management in agricultural landscapes that help to capture and store water and nutrients and their use for meeting crop water requirement (Fig. 1). In addition to store water and nutrient, these wetlands can also remove pollutants from incoming water including municipal and industrial wastewaters and help improve downstream water quality [2]. In arid regions and communities reaching the limits of water availability, water capture, storage and reuse via these systems is an attractive option that may help achieve water conservation and wildlife habitat goals.

*FIG.1. A typical wetland with plants that grow under water logged conditions (courtesy of M.A.M. Shalmani, Islamic Republic of Iran).*

While there is no overall global statistics available for the number of wetlands, the use of these systems in farmlands is increasing continuously throughout the world. In developed countries information on the number, surface area and water column depth for these ponds and wetlands is available. In the United States of America alone there are more than 600 wetlands that receive agricultural runoff, and industrial and wastewater effluent are existing. Similarly, in Australia and other arid regions of Asia–Pacific, wetland constructions are very common for water resource management (harvesting and treating agricultural runoff and their use for irrigation). If planned properly, these wetlands offer opportunities to regain some of the functions of natural wetlands and offset some of the significant losses in wetland area throughout the world. With appropriate siting, design, pre–application treatments, operation, maintenance, and monitoring, these human–made systems can often emulate natural wetlands by providing integrated ecological and socio–economic functions within the landscape and provide water for agriculture and domestic use.

The benefit of water harvesting is not only to secure and increase crop production in semi–arid regions but also to stop soil erosion, recharge aquifers tapped for irrigation and improve downstream water–quality. An underestimated benefit of water harvesting is also the improvement of soil fertility. Silt, manure and other organic matter is "harvested" or kept in place together with the water.

Methods of harvesting water are subject to topography. It is easy to collect surface water and build wetlands in low lands, because surface water flows into such low land areas through gravity. Moreover, ground–water is usually shallow in low lands and easy to extract. Ground–water is a valuable resource because it is not influenced by evaporation and can be pumped easily with simple technologies in low lands. However, pumping too much water lowers the ground–water–level and limits the future supply. When dry weather conditions continue for a long time, water shortages become a problem even in lowlands. Methods for collecting surface runoff effectively are thus important as some of the water harvested helps to recharge the ground–water. Boers and Ben–Asher [3] reviewed technologies for collecting water, but their review was more than 30 years old and might not have sufficient technical information for developing a robust and cost effective harvesting system. Exchange of water between the ground–water and the water harvesting system, enhance the ratio of runoff collection. Systems that also remove pollutants along with water are popular these days and any design needs to consider these additional uses of wetlands.

A wetland is not just a hole in the farm. It is a water conservation area in the farm that requires design, survey, construction, monitoring, evaluation and periodic maintenance. To be effective, a wetland must remain stable during large storm events and the soil must be relatively impermeable (also not completely impermeable) to maintain optimum exchange of water between the wetland and the ground–water underneath the wetland.

Farmer's perceptions of wetlands and water conservation measures are very important determinants of adoption and therefore be carefully considered in addition to profitability for developing these systems in agricultural catchments. From a farmer's point of view, investment to prevent land degradation is costly and shows benefits only in the long run. However, diversification of agricultural activities, which leads to the sustainable use of resources, provides an opportunity to get short–term benefits and reduce farmers' vulnerability to land degradation and economic losses as well as sustaining resources.

Natural processes have always cleansed water as it flowed through rivers, lakes, streams, and wetlands. In the last several decades, systems have been constructed to use some of these processes for improving the capture, storage and quality of water. Wetlands (both manmade and natural) are now used to improve the quality of point and nonpoint sources of water pollution, including storm water runoff, domestic wastewater, agricultural wastewater, and coal mine drainage in addition to storing water. These wetlands improve soil water content in the area surrounding these wetlands. In situ rain-water harvesting is important for staple crops and offers protection in low–rainfall years. But farmers are often put off these technologies because these can be labour–intensive and they lack the necessary capital and training for construction and monitoring.

## 1.2. OBJECTIVE AND SCOPE

The purpose of the guidelines is to provide basic information on the benefits of using wetlands in farm catchments to capture and store water and nutrient, reduce diffuse pollution and enhance biodiversity. The aim is to provide guidance on the options, suitability, placement, design, construction and cost of farm wetlands that help farmers to have sufficient water throughout the growing period, while reducing downstream water–quality degradation and provide eco–system benefit. They are intended to provide basic information for policy makers, project designers and farmers for developing wetlands in agricultural farmlands as well as catchments. They are aimed at making ecologically sound development decisions on water management which pay greater attention to improved water capture, storage, and sustainable use of wetlands in the arid and semi–arid regions [4].

## 1.3. STRUCTURE

This TECDOC provides information on the following, and is briefly described in subsequent two Sections. In Sections 2 to 16, a detailed description of (1) wetland overview, (2) the role of soil, vegetation and hydrology, (3) biogeochemical processes in wetlands including nitrogen (N) and phosphorus (P) cycles, (4) factors to be considered for establishing wetlands, (5) wetland planning, (6) design consideration, (7) construction, and (8) monitoring is provided. The role of isotopic techniques is also described for assessing the performance of wetlands to capture and store water and nutrient. In the Annexes, case studies on the role of isotopic techniques for assessing the performance of wetlands with examples from People's Republic of China, Islamic Republic of Islamic Republic of Iran and Tunisia are provided.

The scientific basis for wetland with functional and structural characteristic including the roles of soil, vegetation and hydrology are discussed in Sections 3 and 4. A detailed description to wetland water budget with biogeochemical cycling is also provided in these Sections. Nitrogen and phosphorus (P) dynamics in wetlands including microbial interactions, the role of microorganisms in nitrification and denitrification and the use of nitrogen–15 for denitrification assessments are discussed in Sections 5 to 7.

Sections 8 to 11 are focused on wetland development consideration including factors such as wetland objectives, land use and climate, identifying functions offered by wetlands under consideration, a risk management strategy in the event of any chance of wetland failure. A conceptual wetland planning which is important for the successful operation of the system and the basic design requirement of wetlands are discussed in these sections. These include a detailed environmental planning for the wetland and site evaluation for optimising the design, construction and operation. The constraints and opportunities for the right wetland for a particular landscape are also analysed in these sections.

Factors to be considered in developing a concept design including a preliminary concept design are discussed in Sections 12 and 13. The design that provides performance efficiency and minimum maintenance are included in these Sections. The detailed concept design includes wetland zone and hydraulic configurations are further detailed in these sections. Catchment runoff and wetland size are determined as part of the detailed concept design are also discussed in these sections. Examples for calculating wetland area are also being provided for readers in these sections.

Information on wetland construction planning and management, vegetation establishment, and erosion and sediment control measures are provided in Section 14. This planning is followed by construction techniques. For example, the importance of site preparation, planting preparation, site restoration, soil preparation, its placement and compaction, and establishing structures are described.

The wetland management, operation and maintenance and monitoring the performance of wetlands are described in Sections 15 and 16. The importance of a monitoring plan for improving the operational performance is also discussed in monitoring wetlands.

Examples of case studies are provided for three countries with the use of isotopic techniques for assessments in Annexes I to IV. In Annex I, isotopic techniques of $^{2}H$ and $^{18}O$ for identifying sources and sinks of water in catchments are discussed. The importance of farm wetlands for water harvest and isotopic techniques for identifying the ideal location for farm wetland in Tunisia are discussed in Annex II. In the second case study (Annex III), isotopic techniques are used to characterise farm wetlands for water harvest and nutrient removal in the Islamic Republic of Islamic Republic of Iran. The third case study (Annex IV) was carried out in the People's Republic of China. Data from this case study showed that the Sanjiang Plain aquifer is significantly recharged by the high altitude precipitation from the surrounding mountain. However, in the unconfined area, extra recharge exists and the ground–water system is recharged from the land surface by rainfall or by infiltration from rivers, irrigation or a combination of each.

## 2. WETLAND OVERVIEW

Wetlands are unique and sensitive ecological systems that play a valuable role as a transitional zone between terrestrial and aquatic ecosystems, sometimes known as buffer zones [5]. Functionally, wetlands play important roles in flood conveyance, flood storage, sediment control, nutrient removal for water and nutrient retention. Other functions include recreation, waterfowl and wildlife habitat. Wetlands can be found along coasts, creeks, rivers, and in forests. They can also be found at any place where saturated soil conditions are necessary for wetlands' development (farmlands). They can naturally exist in farmlands and also be constructed for water harvesting, mainly in dryland farming systems.

Wetlands are dynamic and complex systems that interact with the surrounding environments including the human [6]. The functions and the performance of wetlands depend on the (1) abiotic systems, (2) functional characteristics and (3) structural characteristics of the wetland.

The abiotic system includes hydrology, geomorphology and the substratum (soil). The term substratum is used because in some wetlands (particularly the constructed wetlands) other gravel materials can also be used in the top layer of the bed replacing soil.

The functional characteristics include fluxes of matter and energy (photosynthesis by plants), transformation and uptake of nutrient and organic matter.

The structural characteristics include species diversity and abundance, and gradient and zoning in species. For a specific wetland, a clear appreciation of which socio–economic (provision of matter, energy and water) and ecological goods and services the wetland is providing and a good understanding of how these are linked to the ecological condition, are prerequisites for establishing a performing wetland.

Wetlands are characterized by the presence of three basic parameters: soils, hydrologyo and vegetation and these determine the performance of a wetland. Water is present at the surface or within the root zone for at least a portion of the growing season. As a result of the saturated conditions, the soils present in wetlands develop characteristics that are different from those of upland soils. Consequently, wetlands support vegetative species that are adapted to living in wet and saturated conditions. The following sections will provide thorough discussion on these parameters.

Traditionally, those involved in designing wetlands have to search through a large number of information to determine the basic design principles or guidelines. There have been a number of published manuals or guidelines available for developing wetlands that have different purposes [7–14 ]. Optimisation of wetland performance can potentially be achieved by (1) enhancing the knowledge on biogeochemical processes occurring within wetlands, and (2) systems approach to the design, build and operate through well–defined paths and tasks that are carried out in a logical sequence.

## 2.1. ROLE OF SOIL, VEGETATION AND HYDROLOGY

The physical, chemical and biological characteristics of soils determine its suitability to be used for wetland construction. They are the foundation for and principal storage unit for all biotic and abiotic components of the wetland. It supports vegetation and microbial growth and provides the ideal environment for water–quality treatment. Further information on soils related to their physical and chemical characteristics and suitability for wetland construction is provided in Section 10.2.2.

## 2.2. WETLAND VEGETATION

The role of vegetation in wetlands is to provide a vegetative mass that reduces rate of water flow and sites for microbial development. Dead plant biomass creates litter and release organic carbon that helps microbial activities. Plants also stabilise substrates (soil) while enhancing its permeability and add to the aesthetic value of the wetland.

Wetland ecosystems support plant communities dominated by species that are able to tolerate either permanent or periodic saturation. In general, plants can be divided into either (1) herbaceous or (2) woody vegetation.

### 2.2.1. Herbaceous

These are soft–stemmed plants devoid of woody tissue that often dies back to the soil surface on an annual basis. Based on types of life forms, herbaceous wetland plants can be divided into: (a) hydrophytes that are attached to the soil or sediment substrate and (b) those species that are free–floating. These include emergent species, floating–leaved plants, and submerged plants.

(1) Emergent plants are those species in which at least a portion of the foliage and all of the reproductive structures extend above the surface of any standing water. The plants that are most often used in wetland development are persistent emergent plants. Typical of this type of plant include cattails (*Typha* sp.), rushes (*Juncus* sp.), and sedges (*Carex* sp.). Emergent species are usually found in shallow water or on saturated soils.
(2) Floating–leaved plants have leaves that float on the surface of the water and are attached to the bottom by long stalks. Typical of this type of plant are water lilies (Nymphaea sp.) and spatterdock (Nuphar sp.). Floating herbaceous hydrophytes are those species, such as duckweed (Lemna sp.), that float on the surface of the water and do not contact the underlying substrate.
(3) Submerged plants are those species in which all foliage is underwater. These include eelgrass (Zostera sp.) and pondweed (*Potamogeton sp.*).

Not all wetland plant species are suitable for all types of wetlands. Some plants are not suitable for wetland that receive wastewater from treatment plants since plants for such wetlands must be able to tolerate the combination of continuous flooding and exposure to wastewater or storm water containing relatively high and often variable concentrations of pollutants.

Any species that will grow under flooded conditions well can be chosen. For wetlands, species can be chosen to mimic the communities of emergent plants of nearby natural wetlands.

### 2.2.2. Woody plants

These species are generally divided into (1) trees (greater than 20 feet tall) and (2) shrubs (3–20 feet tall). Trees and shrubs are generally found on exposed, saturated soils, though in a few exceptions (bald cypress, *Taxodium distichum*) they can be found in standing water.

Woody wetland species generally are characterized by physiological features, such as knees, adventitious roots, prop roots, expanded lenticels, and buttress swellings that allow for the interchange of oxygen in water saturated and anaerobic conditions. Some of the more common wetland trees and shrubs include maples (*Acer* sp.), gums (*Nyssa* sp.), willows (*Salix* sp.), mangroves (*Rhizophora* sp.), and blueberry (*Vaccinium* sp.) and are not important for wetlands in farmlands and will not be discussed further.

Bottomland hardwood forests are river swamps. They are found along rivers and streams, generally in broad floodplains. These ecosystems are commonly found wherever streams or rivers at least occasionally cause flooding beyond their channel confines. They are deciduous forested wetlands, made up of different species of Gum (*Nyssa sp.*) and Oak (*Quercus sp.*) and Bald Cypress (*Taxodium distichum*), which have the ability to survive in areas that are either seasonally flooded or covered with water much of the year. Bottomland hardwoods serve a critical role in the landscapes by reducing the risk and severity of flooding to downstream communities by providing areas to store floodwater. In addition, these wetlands improve water–quality by filtering and flushing nutrients, processing organic wastes, and reducing sediment before it reaches open water.

Submerged and emergent wetland plants provide a structural habitat to which microorganisms (algae, epiphytes and other biofilms) can attach and feed. The biofilms also filter and consume soluble pollutants while plants slow velocity and increase hydraulic residence time (HRT) and promote sedimentation.

Maximising the surface area of wetland plants in contact with the water column increases the available habitat for microorganisms which in turn enhances pollutant removal. Plant root, shoot and the available litter and its decomposition affect microbial activity in the wetland system and enhance pollutant removal.

## 2.3. HYDROLOGICAL PROCESSES RELATED TO WETLANDS

The construction, size and functions of wetlands are controlled by hydrological processes. The type of wetlands, their distribution, vegetation composition and soil types in wetlands are primarily influenced by the geology, topography, and climate of the wetland location. The wetland soils and vegetation alter water velocities, flow paths and chemistry and are influencing the overall performance of wetlands. The hydrological and water–quality functions of wetlands, which change the quantity and/or quality of water moving through them, are related to the wetland's physical setting. So identifying the right location determines the correct wetland hydrology and is important for influencing wetland performance. Therefore, the hydrology of a wetland system is perhaps the most important factor to capture and store water and nutrient, and pollutant removal.

While the design of conventional wetland systems is usually based on hydraulic residence time (and therefore water volume), some wetland systems show a more consistent correlation with area and hydraulic loading rate than with hydraulic residence time. This seems reasonable since a wetland is a shallow water system with large surface area in relation to its volume, and receives energy inputs (sun, rain, propagules, gases) on an area basis that is not related to volume. Also, because of the depth limits of wetland plants, the biomass of microbes attached to plants and sediments does not increase proportionally to depth except in a narrow range. So any guidelines pertaining to wetland hydrology are tentative and are in general same processes that occur in any other hydrological cycle [15].

Major components of the hydrologic cycle are precipitation, surface–water flow, ground–water flow, and evapotranspiration ($V_E$). Wetlands receive or lose water through exchange with the atmosphere and ground–water. Both a favourable geologic setting and an adequate and persistent supply of water are necessary for the existence biological processes of wetlands. In general, wet and dry cycles in most wetlands are closely related to lake and river water–level fluctuations [16].

If a land area is covered with water, or if there is saturation of water to the surface in most years (>50% of time) for more than 12.5% of the growing season, then the area is definitely a wetland based on hydrology [15]. If water is present for 5–12.5% of the growing season then it may or may not be a wetland depending upon the other parameters (hydrophytic vegetation and hydric soils). Areas with standing water or water saturation to the surface for less than 5% of the growing season will not meet the definition of a wetland. The major hydrological characteristics of wetlands are briefly discussed in the following sections.

### 2.3.1. Precipitation ($V_p$)

In many locations, particularly in the tropics, arid and semi–arid areas the main form of precipitation is rain which may fall either directly on to the wetland or to the surrounding land area that flows to the wetland as runoff. In cold regions, snowfall to wetland basins provides water to wetlands during spring snowmelt. During rainfall and snowmelt periods the ground–water in the region may also be recharged, sustaining ground–water discharge to wetlands during summer, autumn and winter. The global distribution of rainfall is affected by climate patterns. Mountain slopes and tropical areas generally receive good rainfalls compare to continental interior of the land. Wetlands are generally present in abundance in areas with high precipitation. The downstream of these high precipitation areas also have considerable number of wetlands.

### 2.3.2. Evapotranspiration ($V_E$)

Water loss from wetland to the atmosphere is an important component of the wetland water budget. In wetlands, water is lost by evaporation from water surface and transpiration through plants. In open water wetlands (also called pond) without plants, water loss is mainly through evaporation. Evapotranspiration ($V_E$) is affected by a number of factors including solar energy, wind speed, relative humidity, available soil moisture, and vegetation type and density affect the rate of $V_E$. Evaporation can be measured fairly easily using evaporation pans, shallow ponds and reservoirs, and energy balance concepts. However, $V_E$ measurements, which require measuring how much water is being transpired by plants on a daily, weekly, seasonal, or yearly basis, are much more difficult to make. For this reason scientists use a variety of formulas to estimate $\boldsymbol{V_E}$ and there is some controversy regarding the best formula and the accuracy of these estimates.

Evapotranspiration in wetlands is highly variable both temporally (seasonal and daily) and spatially (different places and agro–climatic regions). Vegetation growth is an important factor affecting $V_E$ meaning that this loss from wetlands vary with plant species, plant density, and plant status (growing and dead plants). Seasonal changes in $V_E$ also affect the water–table levels. When the water table is close to the land surface more water evaporates from the soil or is transpired by plants. The temporal changes in $V_E$ are caused by seasonal changes in atmospheric temperature (more water evaporates or is transpired in hot weather than in cold).

### 2.3.3. Surface water (V)

One of the main features of wetlands is the proximity of the water table relative to the ground surface. In surface waters (including lakes, rivers and marine water systems) the water surface lies on the surface of the land, while in terrestrial landscapes the water surface lies some distance below the plant root zone either as water table or zone of saturation. Wetlands on the other hand occupy the transition zone between predominantly wet and dry environments. The shallow hydrologic environment of wetlands creates unique biogeochemical conditions that distinguish it from aquatic and terrestrial environments. Surface water is supplied to wetlands through normal stream flow, flooding from lakes and rivers, overland flow (collectively runoff flow, $V_s$), precipitation directly falling on to the wetland ($V_p$) and ground–water discharge ($V_{GD}$). Once ground–water is discharged into wetlands it also becomes surface water.

Surface water outflow from wetlands ($V_D$) is greatest during the wet season and especially during flooding. Surface water may flow in channels or across the surface of a wetland. Flow paths and velocity of water over the surface of a wetland are affected by the topography and vegetation within the wetland.

Streamflow from wetlands that have a large component of ground–water discharge tends to be more evenly distributed throughout the year than streamflow from wetlands fed primarily by precipitation. This is because ground–water discharge tends to be relatively constant in quantity compared with precipitation and snowmelt.

### 2.3.4. Ground–water ($V_{GR}$)

Precipitation and other surface waters are main sources to ground–water. Precipitation moves slowly downward through the soils and rocks until it reaches the saturated zone (a zone in which the soil is saturated with water) below the ground. Water also seeps from lakes, rivers, and wetlands into the saturated zone. This process is known as ground–water recharge. The top of the saturated zone is called as the water table. Depending upon differences in hydraulic head ground–water to move back to the land surface or into surface–water bodies; this process is called ground–water discharge. Natural wetlands are one of the common areas for ground–water discharge. So it is important to have an understanding on the hydrological connectisvity between the ground–water and the wetland that is proposed to be developed in a particular landscape. This is one of the major criteria for developing a wetland. If a hydrological connectivity exists between the ground–water and the wetland then the wetland will have water throughout the year irrespective of the season and weather and meets the definition of wetlands with water and nutrient retention.

Most commonly wetlands are ground–water discharge areas (moving water from ground–water to wetland); however, ground–water recharge also occurs. Ground–water recharge or discharge in wetlands is affected by topographic position, hydrogeology, sediment and soil characteristics, season, $V_E$, and climate and might not occur uniformly throughout a wetland. Recharge rates in wetlands can be much slower than those in adjacent uplands if the upland soils are more permeable than the slightly permeable clays or peat that usually underlie wetlands. Ground–water discharge will influence the water chemistry of the receiving wetland whereas ground–water recharge will influence the chemistry of water in the adjacent ground–water. A number of isotopic signatures (hydrogen–2, oxygen–18 and hydrogen–3) are useful for the assessment of ground–water and wetland water interaction.

## 3. WETLAND WATER BUDGET

The wetland water budget is the total of inflows and outflows of water in a wetland. The relative importance of each component varies both spatially and temporally, but all these components interact to create the hydrology of an individual wetland [17]. Determining water budgets for wetlands is important because it is useful for developing a management plan that helps to improve the performance of wetlands in terms of water and nutrient capture, their storage and use. The climate varies from year to year and so does the variation in water balances. Therefore long term monitoring of inflows and outflows are important for obtaining long term water budget. The accuracy of individual components depends on how well they can be measured and the magnitude of the associated errors. However, water budgets, in conjunction with information on the local geology and climate, provide a basis for understanding the hydrologic processes and water chemistry of a wetland, understanding its functions, and predicting the effects of natural or human–induced hydrologic alterations. There are three main aspects to the hydrology of a wetland that control its ability to transform and store nutrients. They are (i) the hydrological linkage between the wetland and the wider catchment, (ii) the internal hydrological regime of the wetland and (iii) hydrological pathways within a wetland [18].

### 3.1. WATER BUDGET CALCULATION

A wetland water budget based on input and output is provided in Fig. 2. The amount of water stored in a wetland depends on input and output. If input exceeds output, the water will be stored in the wetland and vice–versa. For a wetland within an agricultural catchment a more detailed water balance is important which involves various components. (Fig. 2)

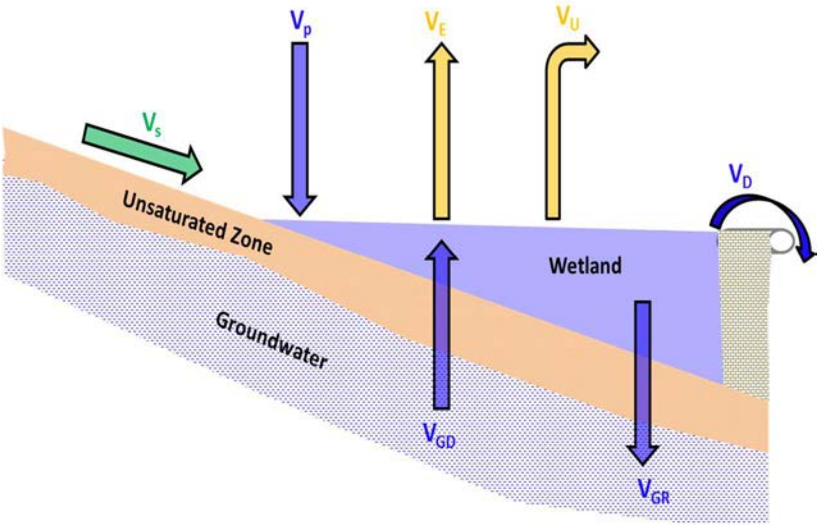



*FIG. 2. Wetland water budget (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

$V_P$ = volume of precipitation directly falling on the wetland
$V_S$ = volume of runoff entering the wetland
$V_{GD}$ = volume of ground–water discharge (amount coming from ground–water to the wetland)
$V_E$ = volume of water lost through evapotranspiration now you refer $V_E$ as water lost through
$V_{GR}$ = volume of infiltration flux (ground–water recharge)
$V_D$ = volume of flow from the wetland
$V_U$ = volume of water used (irrigation)

An ideal wetland captures water during rainfall/runoff period and should also have the potential to interact with the underlying ground–water (recharging the ground–water and receive ground–water discharge). The water budget for wetland provides information on whether the wetland is a sink and/or source of water. All components of the water budget of a wetland are subjected to both short and long term and seasonal variation related to input and output of water and impacts of climate changes or by modification of either natural or human–related to the concerned catchment. Based on the water input and output provided in Fig. 2, the water balance equation for a wetland system that interacts with ground–water in an agricultural landscape is provided by the following equation:

$$D_v = (V_s + V_p + V_{GD}) - (V_E + V_U + V_{GR} + V_D) \tag{1}$$

where:

$D_V$ = water storage variation in the wetland
$V_S$ = volume of runoff entering the wetland
$V_P$ = volume of precipitation directly falling on the wetland
$V_{GD}$ = volume of ground–water discharge (amount coming from ground–water to the wetland)
$V_E$ = volume of water lost through evapotranspiration
$V_{GR}$ = volume of infiltration flux (ground–water recharge)
$V_D$ = volume of flow from the wetland
$V_U$ = volume of water used (irrigation).

This water balance equation is general and is applied to many of the hydrological systems such as dams, reservoirs and small ponds. Readers are advised that the notations and the descriptions for the water balance equations may be different for various systems and depends on authors.

## 4. BIOGEOCHEMICAL PROCESSES IN WETLANDS

Wetlands in agricultural landscapes help to improve water–quality and quantity through a range of physical, chemical and biological processes. They are characterized by a range of properties that make them attractive for managing water, nutrient and other pollutants. These properties include: (1) high plant productivity, (2) sediments with high adsorptive capacity, (3) oxidation associated with microflora, and (4) nutrient and pollution buffering capacity.

Changing environmental conditions in the wetland affect biogeochemical processes. These include:

a) diurnal variations in water temperature and dissolved oxygen concentrations;
b) seasonal variations in plant growth affecting dissolved oxygen levels and pH of water in the system.

### 4.1. MAJOR BIOLOGICAL PROCESSES IN WETLANDS

***Photosynthesis*** is performed by plant and algae and adds carbon to the wetland. The process is active only during day time, but at night the plant releases carbon through respiration.

***Respiration*** is carried out by both plants and living organisms in the wetland. During this process organic carbon is oxidised and carbon dioxide and water are produced eventually releasing carbon dioxide to the atmosphere. The process is occurring during day and night.

***Fermentation*** is performed by microbial activity in the absence of oxygen and the process produce energy rich compounds such as methane, alcohol, and volatile fatty acids.

***Nitrification/denitrification*** removes N from water in the wetland by first oxidising organic N to nitrate and then reduce to nitrous oxide and $N_2$ gas through denitrification. The process is mediated by microorganisms. Nitrogen is also removed from water through the physical process of volatilisation. Further details are provided in Section 6.1.

***Microbial P removal*** occurs within biofilms and adsorption onto sediments. Additional information on P dynamics in wetland is provided in Section 6.2.

In general, bacteria and fungi present in the wetlands remove soluble organic matter, coagulate colloidal materials and convert these into different compounds and new cells. Some of these are gases and are lost to the atmosphere.

### 4.2. CHEMICAL PROCESSES IN WETLANDS

Precipitation of certain chemicals, particularly metals to insoluble forms and settled at the bottom of the water column. Certain organic compounds can be broken in to smaller molecules by exposure to light and atmospheric gases [19].

In wetlands with shallow water column, some organic compounds entering are lost to the atmosphere through volatilisation.

The redox potential of wetland determines the solubility or insolubility of nutrients and some metals in the wetland.

The soil and water pH in the wetland influences the direction of many reactions and processes, including biological transformation, partitioning of ionized and non–ionized forms of acids and bases, cation exchange capacity, and solubility of gases and solids.

### 4.3. PHYSICAL PROCESSES IN WETLAND

The presence of suspended materials in water slows down water flow and the absorbed nutrients settled at the bottom of the water column in the wetland.

The effectiveness of biological, chemical and physical processes depends on the residence time of the flowing water in the wetland. When the water flow is high such as rainfall and flood periods, the wetland effectiveness is very low. However, during low flow (or base flow) period, the treatment effectiveness is high. During high flows, wetland treatment efficiency is not very important as concentrations of incoming nutrients/pollutants are lower.

## 5. ISOTOPIC AND NUCLEAR TECHNIQUES FOR ASSESSING WATER AND NUTRIENT IN WETLANDS

For the effective management of a surface or ground–water, hydrological information is required on (1) source and amount of water contributing to surface and ground–water, (2) the interaction between surface and ground–water, and (3) source, fate and transport of pollutants. Both stable and radioactive isotopes can be used to follow water dynamics, the biogeochemical processes of elements and their quantitative measurements in natural systems. The physical and chemical properties of both stable and radioisotopes help to trace the movement of water and a particular element. While radioactive isotopes emit particles (for example alpha, beta and gamma) and are captured in photomultiplier tubes the stable isotopes are separated by passing a gas containing these different isotopes through a strong magnetic field which deflect these isotopes according to their mass. Most commonly used stable isotopes are hydrogen–2 ($^{2}H$), carbon–13 ($^{13}C$), nitrogen–15 ($^{15}N$) and oxygen–18 ($^{18}O$). Integrating isotopic techniques into hydrological and nutrient management assessments in wetlands are economically and scientifically affective in providing information that helps to optimise the performance of wetlands for water and nutrient capture and storage [20].

The use of $^{2}H$, $^{18}O$ and $^{15}N$ for assessing water and nutrient dynamics are discussed in this document where necessary. These include (1) identifying sources of water to wetlands, (2) interaction between wetland water and ground–water, and (3) nutrient dynamics including crop uptake and denitrification in wetlands.

### 5.1. STABLE WATER ISOTOPES

The oxygen–18 and hydrogen–2 are typically considered as water isotopes. They offer a number of possibilities to study water dynamics. Understanding the isotopic composition of various sources of water (precipitation, runoff, surface and ground–waters) and their spatial and temporal variation are important for basin–wide water balance studies including basins that are part of wetlands.

The evaporation and condensation of water in natural hydrological processes, the fractionation of hydrogen–2 and oxygen–18 are related. The relationship between hydrogen–2 and oxygen–18 in meteoric water is given as "Global Meteoric Water Line" (GMWL) and is defined by the following equation:

$$\delta^{2}H = 8\delta^{18}O + d \qquad (2)$$

An empirical regression relation involving many Local Meteoric Water Lines (LMWL) differs from GMWL in slope and intercept according to varying climate and geographical parameters. The constant d is called deuterium excess and is +10 for the GMWL. This value will be lower or higher depending on the sources, geography and the season. For example, water with d values greater than 10 corresponds to high temperatures and evaporations. The isotopic signatures and d vales are useful to identify sources of water in the wetland.

## 6. NUTRIENT DYNAMICS IN WETLANDS

The transformations of N and P in wetland are compartmentalised into water column, sediments at the bottom of the water column, litter above the soil, and plant biomass. In general the distribution of N and P in these compartments are provided as follows [21, 22].

| | |
|---|---|
| Soils and litter/peat: | 80% |
| Water column: | 15–20% |
| Plant and other biota: | 5% |

### 6.1. WETLAND N PROCESSES

Nitrogen can enter to wetlands in agricultural landscapes through a number of pathways. They include: (1) deposition of atmospheric N on the catchment or directly on the wetland surface, (2) leaching or surface runoff within the catchment, such as those resulting from fertiliser and manure application, (3) erosion of N rich soils, and (4) direct input from point sources such as sewage treatment works. Apart from these sources, N can also enter wetlands through biological N fixation.

Nitrogen cycling in wetlands is complex and involves a variety of N forms and associated oxidation states (Fig 3.). Both the oxidized and reduced inorganic N species ($NO_2^-$, $NO_3^-$, $NH_4^+$, $NH_3$) and organic N fractions such as dissolved organic N (DON) and particulate organic N (PON) are commonly found in wetlands. Nitrate, $NO_2^-$, $NH_4^+$, and DON are directly available for plant uptake, supporting production in plant community [22]. In addition, gaseous forms ($N_2$, $N_2O$, NO) are exchanged with the atmosphere. The primary role of N in wetlands is to support primary production by higher plants and algae and is one of the key nutrients, along with carbon, P and silica.

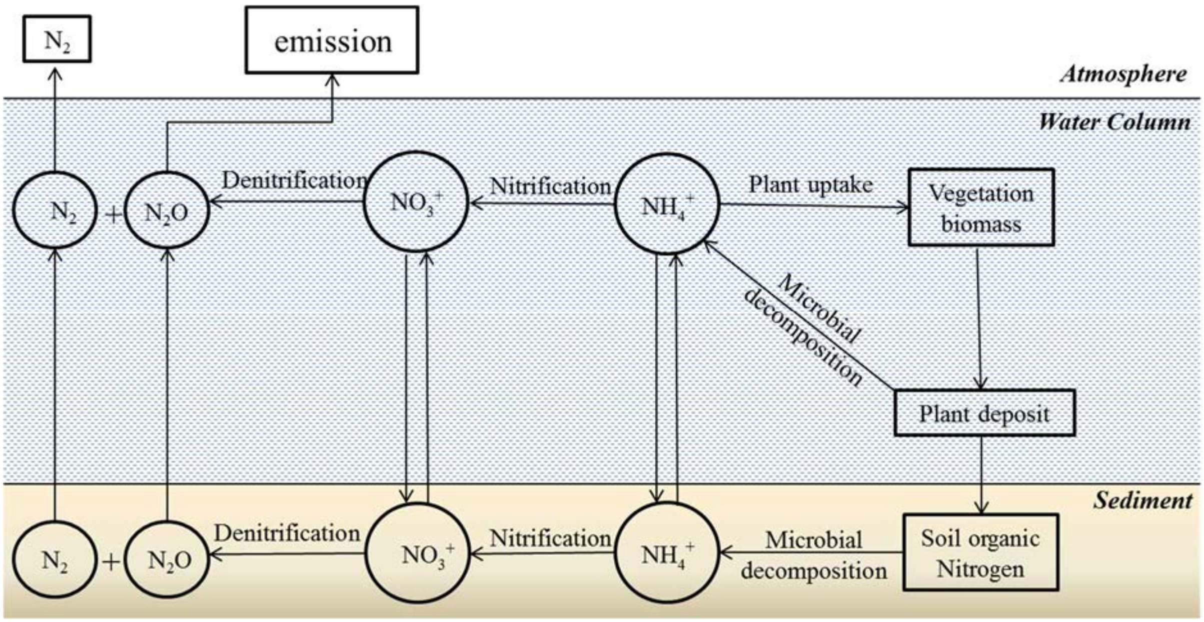



*FIG. 3. A simplified N cycle in a wetland system [22].*

In wetlands the N cycling is controlled by the energy sources (light, organic matter and reduced inorganic compounds such as sulphur or ferrous minerals), redox conditions (oxygen availability) and the nutrient loads. The main factor differentiating N turnover rates in wetland systems, however, is the residence time of the water. The process of N removal in wetlands follows several sequences. Nitrification takes place first generally near soil–plant root zone. Denitrification may then follow, occurring in soils and below the oxidised micro zone at the soil–water interface as the process is anaerobic. The nitrification and denitrification process are briefly described below. For details, refer to [14], [22] and [23]

**Nitrification:** This is a two–step process catalysed by nitrosomonas and nitrobacter bacteria. In the first step ammonia oxidised to nitrite ($NO_2^-$) by nitrosomonas bacteria and then oxidised to nitrate ($NO_3^-$) by nitrobacter:

$$NH_4^+ + O_2 \xrightarrow{nitrosomonas} H^+ + NO_2^- + H_2O \qquad (3)$$

The liberation of hydrogen ion creates acidic conditions and affects denitrification products, particularly in acid soil conditions.

The nitrite produced is then aerobically converted into nitrate by nitrobacteria:

$$NO_2^- + O_2 \xrightarrow{Nitrobacter} NO_3^- \qquad (4)$$

Some environmental factors affect nitrification process with implications for wetland performance. For nitrification to occur there needs to be sufficient dissolved oxygen (DO) in water of wetlands. Wetlands receiving water with dissolved organic carbon (biological oxygen demand of more than 20 mg $L^{-1}$), the DO is low and as a result the nitrification process is slow.

The vegetation used in wetlands, temperature and the retention time of water in the wetland are also important factors affecting nitrification. For example, during summer and at low flows the rate of nitrification in the wetland may be enhanced as a result of higher water temperatures and water retention time. The presence of vegetation provides oxygen through respiration and enhances the dissolved oxygen concentration of the wetland water and influence nitrification.

**Denitrification:** Nitrate is reduced under anaerobic conditions to gaseous forms for N such as $N_2O$, NO and $N_2$. The process is characterized by denitrifying bacteria *Pseudomonas spp.* and other bacteria:

$$NO_3^- + Organic - C \xrightarrow{Denitrifying\ bacteria} N_2 + N_2O + CO_2 + H_2O \tag{5}$$

The location of a wetland in the landscape is very often the crucial factor in determining its effectiveness as an area for N transformation [24]. The assessment of the impact of wetlands on N flux at the landscape scale has focused on the total area of the wetland. However, in wetlands the active zone of transformation is the wetland/landscape interface (related to reduction of nitrate concentrations in inflowing water).

The location of nitrate removal at the upslope edge of a wetland receiving water from the hillslopes is explained by the combination of high nitrate concentrations in the runoff , high carbon concentrations in the soil (essential as a respiratory substrate for the denitrifying bacteria), and anaerobic conditions resulting from elevated water table. This combination provides optimal conditions for denitrification to occur in wetlands [25]. Nitrate concentrations are sometimes depleted over a few metres within this zone, and the rest of the wetland often shows very low denitrification rates [26]. As a consequence, the length of interface between the wetland and upslope sources of nutrient rich runoff is often an important factor determining the impact of the wetland on nitrate reduction.

Although the role of wetlands on N flux has been widely documented, the complete environmental assessment of increased N loads in wetlands must include the potential limitations and adverse effects N on the environment [27]. For example, increased $N_2O$ emission rates due to higher N availability and denitrification favouring conditions are likely to occur. Factors such as acidic conditions and low temperatures further alter the $N_2O/N_2$ ratio in the denitrification process. Increased $CO_2$ emissions are likely as well, due to increased organic matter oxidation in these systems. Another side effect is the release of dissolved organic carbon (DOC) and dissolved organic N (DON) into the downstream water [28]. Finally, increased N load can damage the ecological status of the wetlands leading to reduced biodiversity and alter the structure and functions of wetland ecosystem Therefore, wetland design needs also consider options to reduce such negative impacts, particularly the emission of $N_2$ rather than $N_2O$.

### 6.1.1. Nitrogen–15 for denitrification assessments

There are two stable isotopes of N, namely $^{14}N$ and $^{15}N$. The most common isotope is $^{14}N$ which accounts for approximately 99 percent of atmospheric N and $^{15}N$ accounts for 0.36%. Although the N isotopic composition of the standard atmospheric $N_2$ is constant, other materials have variable isotopic compositions because some biological processes discriminate (i.e. fractionation during biochemical transformation) between N isotopes. The lighter isotope ($^{14}N$) often reacts more rapidly in biogeochemical cycles than the heavy one ($^{15}N$); therefore processes involved in the N cycle can also affect the ratio between the $^{15}N$ and $^{14}N$ isotopes in environmental N pools. Among these processes, microbial denitrification significantly alters the N isotope ratio, resulting in the progressive enrichment of the remaining $NO_3$ pool with $^{15}N$ [29, 30]. In contrast to denitrification, $NO_3$ uptake by terrestrial vegetation appears to fractionate minimally or not at all.

Examples of the use of $\delta^{15}N$ to decipher the respective role of denitrification and plant uptake in N buffering capacity of riparian zones has been provided by a number of studies that include [31]. They used the natural abundance distribution of N isotope in both the ground–water $NO_3$ and riparian plant tissues along transects to determine the extent of ground–water $NO_3$ decline that resulted from denitrification and/or plant uptake. They found that the decline in ground–water $NO_3$ concentration along flow paths under the riparian zone was correlated to an increase of $\delta^{15}N$ in the remaining $NO_3$ in ground–water, indicating that denitrification was the main process responsible of $NO_3$ decline. However, analysis of $^{15}N$ in plant growing along the water transect showed a good relationship with $\delta^{15}N$ of ground–water $NO_3$.

The isotopic signatures of $^{15}N$ and $^{16}O$ ($\delta^{18}O$ and of $\delta^{15}N$) in $N_2O$, the bulk $^{15}N$ (the total $^{15}N$ signature in $N_2O$, $^{15}N^{bulk}$–$N_2O$) and $^{15}N$ from the central N position ($^{15}N^{\alpha}$), are all useful for measuring both $N_2$ and $N_2O$ emissions form wetlands and their sources [32].
The site preference (SP‰) $^{15}N$ (i.e. the $^{15}N$ in the $N^{\beta}$ position of $N_2O$) was obtained using the following equation:

$$SP = 2(^{15}N^{\propto} - {}^{15}N^{bulk}N_2O) \quad (6)$$

where $^{15}N^{\alpha}$ and $^{15}N^{bulk}N_2O$ are isotopic ratios of N in the α position and the bulk of the $N_2O$, respectively. This showed that importance of isotopic techniques for assessing the sources of $N_2O$ emission and estimate $N_2$ emission relative to $N_2O$.

## 6.2. WETLAND P PROCESSES

Wetlands are capable of absorbing P, and, in appropriate circumstances, can provide a low–cost alternative to chemical and biological treatment. Phosphorus interacts strongly with wetland soils and biota, which provide both short–term and sustainable long–term storage of this nutrient. Soil sorption may provide initial removal, but this partly reversible storage eventually becomes saturated [33]. Uptake by biota, including bacteria, algae, and duckweed, as well as macrophytes, forms an initial removal mechanism.

Phosphorus can enter wetlands in dissolved and particulate forms (bound to soil particles) and organic particles derived from soil and plants. Wetland processes can alter the forms of P depending on the pH of the water and the presence or absence of dissolved oxygen.

Under acidic conditions, phosphates of aluminium, iron and manganese form precipitate and are highly insoluble in water. Also under acid conditions some phosphate may be associated with clay. At pH levels more than 6, calcium phosphate can form and precipitate. Dissolved inorganic P (orthophosphate) can occur by the dissociation of phosphoric acid ($H_3PO_4$) as follows:

$$H_3PO_4 \rightarrow H_2PO_4^- + H^+ \rightarrow HPO_4^- + H^+ \rightarrow PO_4^- + H^+ \quad (7)$$

Due to the general scarcity of P in most natural environment, and the absence of significant atmospheric source, wetlands have numerous adaptations to sequester available P. Therefore wetland configuration can also include the provision for extensive uptake of P through biofilm and plant growth, sedimentation and filtration of suspended material.

In general, the P cycle is efficient and extensive in wetlands (Fig. 4). The P fluxes between each compartment are dependent on (1) redox chemistry, (2) pH, and (3) temperature. The redox status (related to the presence of dissolved oxygen in water) of sediment and the litter peat compartment determines the particular P transformation process. When the dissolved oxygen concentration is low (reduced condition), sediment/soil liberates P into the water column and leave the wetland through outflow if the reduced oxygen condition in the wetland is not reversed.

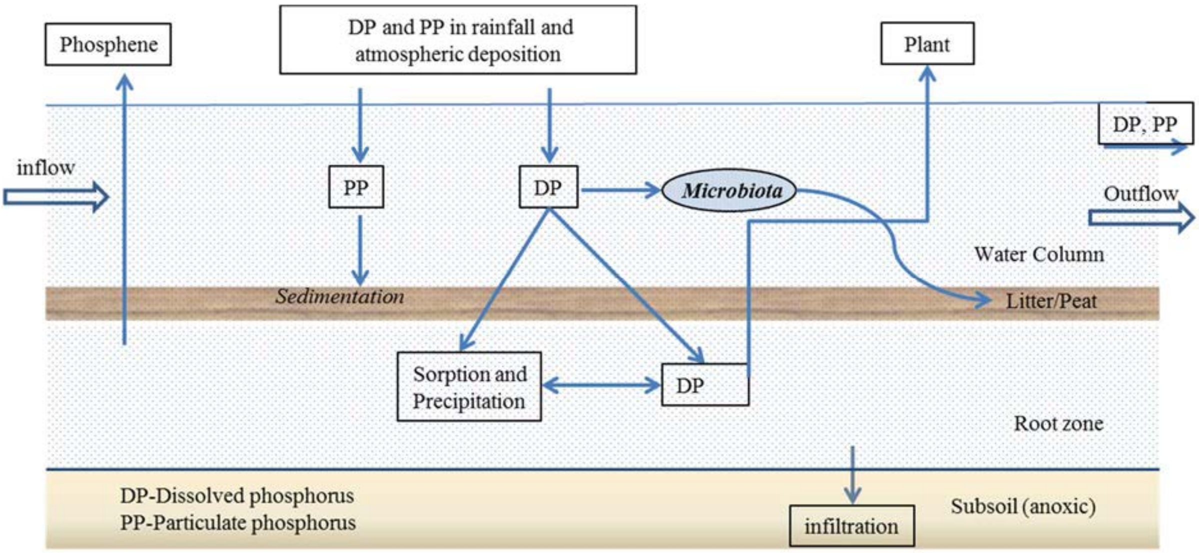



*FIG.4. Simplified P cycle in a wetland [34].*

Plants take up P from the sediment and water column during the growth period, but release it to the litter/peat compartment during senescence, death and decomposition. Primary P removal mechanisms are (1) adsorption, (2) filtration, and (3) sedimentation. Other secondary removal processes include precipitation/complexation and assimilation/uptake by biota.

During adsorption, P bound with metals, mainly iron and aluminium in the soil solid particles. They can also adsorbed by inorganic salts such as calcium carbonate. Soils with appreciable clay content have very good P adsorption capacity, but it is to be noted that they have finite number of sites for adsorption.

During sedimentation, particulate materials with P sink and accumulate on the floor of the wetland (surface of the soil layer). Particulate material may be reactive (undergoes decomposition) or non–reactive. For reactive particulate matter, the P may be released to water column after decomposition. In the case of non–reactive, the sedimentation process is permanent and P is not released to the water column. Under oxygen limiting conditions, particulate P may be released as soluble form to the water column.

Organic P, orthophosphate and polyphosphates are absorbed by accumulating in wetland sediments. However, their subsequent release to water column depends on the redox potential. As stated earlier, the reducing conditions caused by low dissolved oxygen levels allow absorbed P to be released. This process can be prevented by maintaining high oxygen level in the water column. This can be achieved by maintaining continuous water flow in the wetland and allow sufficient plant cover for the movement of oxygen into the root zone.

Aluminium, calcium, iron and manganese can form complexes with P and these compounds co–precipitates to the sediments with other minerals [13]. The water column pH is an important factor in mediating this process. Under acidic conditions, it combined with aluminium and iron. In alkaline conditions, P combines with calcium and magnesium forming complexes and precipitate.

Wetlands buffer the P interactions among uplands and adjacent aquatic systems. It is often the key nutrient found to be limiting in both estuarine and freshwater. As such, the ability of wetlands and to retain P is key to determining downstream water–quality. Although complex numerical models are available to estimate P retention and transport, a simple understanding of P retention at the process level in wetlands is important, but the overall picture provided by mass–balance and kinetic evaluations are often more useful in estimating long–term P retention [35]. Therefore when designing wetlands in agricultural landscapes, it is important to consider the P removal capacity of wetlands by selecting appropriate substrate (e.g. the soil- used as the bed material).

## 7. FACTORS TO BE CONSIDERED FOR ESTABLISHING A WETLAND

A number of factors affect the performance of wetlands and their socio–economic values such as the capacity to harvest water and nutrient, improve water–quality, and the environmental, economic and cultural values are briefly discussed below.

### 7.1. WETLAND OBJECTIVES

The wetland objectives determine the configuration and shape of each component within the wetland which include water quantity and/or quality control, ground–water recharge/discharge and socio–economic and environmental benefits.

### 7.2. LANDSCAPE AREA, CLIMATE AND RAINFALL

The area of the catchment that feeds water into the wetland determines the volume of water and pollutants enter into the wetland. The size of the wetland will depend on the landscape size. Seasonal variations in climate are critical to the selection and establishment of wetland plants. Rainfall influences hydraulic residence time and pollutant loading. Landscape topography determines sufficient land availability for construction.

### 7.3. LAND USES

The amount of water generated in a landscape depends on the land use in the landscape. Depending upon the proportion of forest, pasture and cropland runoff generated. In general, forest produces minimum runoff followed by pasture and croplands. For infiltration, the reverse occurs. In addition, if the landscape contains buildings and pavements, the runoff generation increases and affects the size of the wetland being developed.

### 7.4. OTHER FACTORS

These could include endangered and threatened species present in the area, land ownership, service utilities and topography, all of which will affect the land available for wetland development.

These factors need to be carefully considered for successful implementation of a wetland system in agricultural landscapes.

## 8. PREDESIGN ASSESSMENT FOR WETLAND DEVELOPMENT

The first step in wetland planning and design is to develop the objectives and functions offered by the wetland (e.g. water harvesting, nutrient removal, eco–system services). Once the objectives and functions are established, an understanding of the baseline conditions of the wetland is important as it allows identifying whether the wetland can perform the required functions once established [36].

The second step is to look at the potentially impacted area. The three important parameters that generally define the boundaries of the wetland are the presence of plants, soils, and hydrology that are typical to wetlands.

## 8.1. RISK MANAGEMENT

In the event that an unavoidable impact (flooding and bank erosion leading to leakage) to the wetland must occur, a detailed understanding of the entire wetland be developed to lay the foundation for sound mitigation planning. This mitigation planning includes the preparation of plans based on a detailed understanding of site conditions and project objectives.

The ability to successfully create wetlands, whether on or off site, is dependent upon a detailed characterisation of the wetland to be impacted. The characterisation may include not only the physical features of the wetlands, but by extension, the functions that the wetland offers. The failure to define goals and objectives of wetland development and the failure to state quantifiable measures of success can lead to the failure of the wetland functions.

One common cause of wetland failure is a problem with site hydrology. As hydrology is a defining parameter in wetlands, an understanding of the hydrology of the wetland site is essential to the success of the wetland development. Design and construction deficiencies may also lead to the failure of hydrology and wetland functions. Identifying site–specific planning requirements is recommended for wetland construction. A pre design decision tree that covers all aspects of wetland development from the initial concept to the final development needs to be developed before the planning for wetland can be started (Fig. 4).

# 9. WETLAND PLANNING

A conceptual planning phase for the wetland development is essential. This can be undertaken prior to or during the concept development stage. Wetlands can be designed in a variety of system types and configurations to meet specific objectives, alternative sites are often available, and a variety of local, native plant species can be chosen. Every site is unique and the design of a wetland system will be site–specific and depends on its objectives.

The planning phase consists of (1) characterising the quantity and quality of the water to be captured and stored and if necessary cleansed, (2) determining the discharge standards to be met, (3) selecting the site, system type and configuration, and (4) specifying the design criteria to be met by the detailed engineering plans. Economic factors including the land area required are also important during the design phase. The characteristics of locally available natural wetlands may be used as a model for the wetland to be developed, modified to fit the needs of the wetland objective to site specific characteristics.

The wetland is designed to take advantage of the natural features of the site and to minimise its disturbance. Wetland shape is dictated by the existing topography, geology, and land availability. Before constructing a wetland in an agricultural landscape it is important to develop a pre–design decision tree to characterise and determine the major purposes of the wetland (Fig. 5).

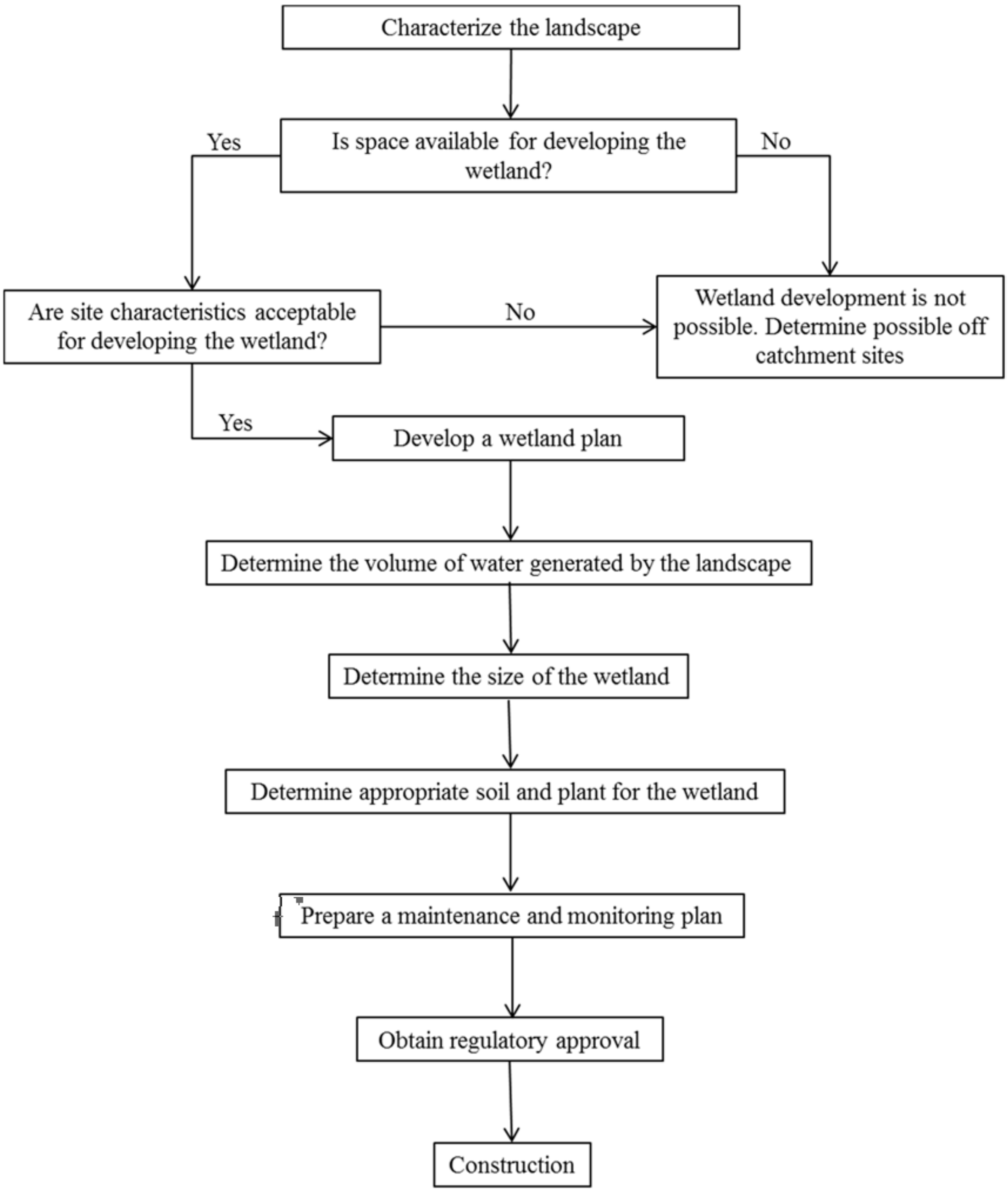



*FIG. 5. Decision tree for wetland development.*

## 9.1. DESIGN REQUIREMENTS

Basic requirements for a successful wetland development are:

(1) Consider the hydrogeomorphic and ecological landscape and climate in designing wetland and its conservation.
(2) Locate the proposed wetland site in an appropriate landscape position and hydrogeomorphic classes that meet the following characteristics:
    (a) Consider both current and future watershed hydrology of the landscape, and select sites that are resistant to disturbance from the surrounding landscape in terms of flood, erosion and sedimentation and ground–water movement,
    (b) Restore or develop naturally variable hydrological conditions.

(c) Whenever possible, develop a wetland with minimum disturbance to landscape hydrology and ecology avoiding over engineered structure with long term sustainability and minimum maintenance.
(d) Pay close attention to provide heterogeneous topography, appropriate planting elevation, depth, soil type, and seasonal timing.
(e) Pay close attention to subsurface conditions such as soil and sediment geochemistry and geophysics, ground–water–quality and quantity.
(f) Consider complications associated with developing wetlands in seriously degraded or disturbed sites.

A number of strategic planning is important that can result in the identification of the wetland as a land–water management option. Some important planning that are relevant to agricultural water management include (1) catchment management plan, (2) planning for specific habitats, (3) education and research opportunities, (4) environmental flow maintenance, and (5) retrofitting opportunities.

## 9.2. PLANNING CONSIDERATION FOR FARM DAM WETLANDS

For wetland construction in farm lands the following issues may be considered during the planning stage:

(a) Wetlands in farmlands are affected by the farm and catchment land uses. Initial planning consideration should explore both the reasons for implementation and the potential problems. These problems may be addressed to varying extents through the development and implementation of management plans which may include actions such as control over land use and establishing buffer zones around the wetland. These actions minimise nutrient and sediment inputs to the wetland.
(b) The wetland could not be a system on itself, but part of a wider catchment or farm management plan including agricultural water management providing multiple benefits such as water harvest, its use for irrigation, downstream pollution control and habitat conservation. In general, the wetland is developed to provide multiple objectives.
(c) The various objectives of wetlands need to be developed in consultation with all stakeholders, in particular stakeholders involved in downstream water management. Pollution control approval from relevant authorities is important.

## 9.3. ENVIRONMENTAL IMPACT ASSESSMENT ISSUES FOR DEVELOPING WETLANDS

During the design phase extra attention is required for several environmental issues. These related to the site of the proposed wetland, the downstream areas, within the farm and the wider catchment. Some common issues are provided below.

- Wetland values;
- Erosion control;
- Channel stability;
- Soil amelioration;
- Protection of ground–water resources;
- Protection of terrestrial flora and fauna;
- Accumulation of metals and agro–chemicals;
- Aquatic weeds;
- Pest species;

- Downstream water–quality and quantity;
- Impact of the local community.

## 10. SITE EVALUATION

The evaluation of the site for wetland development in a farm land is important for optimising its design, construction and operation. Existing information available for the site (farm land) and data collected during site visit for investigation are used for evaluation. These site evaluations provide opportunities to identify potential constraints and opportunities of the site for developing the wetland.

Site suitability determines whether a particular site in the farmland is capable of supporting a wetland. Based upon existing and new information an assessment of the suitability needed to be carried out for the site. The suitability of the site will be based on the assessment of constraints and opportunities of the site for wetland development. Constraints and opportunities are determined during site investigation and evaluation.

### 10.1. CONSTRAINTS AND OPPORTUNITIES

A preliminary analysis of constraints and opportunities is part of the concept development phase. Constraints are grouped as 'general' or 'physical'. The general constraints include (1) the need for health and safety (human and livestock), (2) the finances available for developing the wetland, and (3) relevant policies and legislation. Physical constraints can be identified from site information including soil characteristics (physical and chemical) and hydrology.

Investigations to determine constraints can be carried out by the following three steps:

(1) Checking relevant policies and legislations to assess the level of detail necessary for site investigation.
(2) Collecting data on soil characteristics, topography of the area, geomorphology, surface hydrology, water–quality, ground–water depth and quality, climate and biological resources including vegetation survey.
(3) Public health and safety and livestock welfare.

During the design process it is possible to overcome some constraints through modification to the design to minimise constraints. Typical site constraints and opportunities and their impact wetland construction are provided in Table 1.

TABLE 1. CONSTRAINTS AND OPPORTUNITIES FOR WETLAND CONSTRUCTION

| Constrain | Impacts |
|---|---|
| Long distance from source of inflow | Cost associated with diverting water to the wetland |
| The presence of gravel or rocks | Leaking of water from wetland to subsurface |
| Presence of suitable soils | Substantial cost associated with importing soil. |
| Depth to ground–water | With shallow ground–water depth (<2 m) difficulties may occur with compaction during construction |
| Infrastructure present beneath the surface | Cost of relocation |
| **Opportunities** | **Impacts** |
| Prominence (close to main roads) | Attractive for educational opportunities and public visit |
| Strategic location with farm land and catchment | As a demonstration site for water harvest pollution control in the catchment |
| Site in need of rehabilitation | Maintain any existing wetland features |
| Adjacent to wildlife corridors/ habitat areas | Incorporate into landscape design, enhance potential to attract wildlife |

## 10.2. SITE INVESTIGATION

Before any wetland development occur, it is important to critically analyse the characteristics of the site. These include topography, soil, geology/geomorphology, hydrology, surface water–quality, ground–water, biological resources, climate, public health and safety consideration.

### 10.2.1. Topography

Topography will influence construction costs, cut and fill requirements, erosion potential, drainage patters, access and overall feasibility. A wetland is ideally being gently sloping (2–6%). Steeper slopes are also useful for developing terraced wetlands.

Topographic information can be obtained from maps (topographical and cadastral), photographs and geographic information systems (GIS). If information is not available then a topographical survey is required.

Contour intervals for topographic assessment are between 0.1 to 0.5 m depending on the nature of the topography and the size of the wetland.

The topographic survey data are entered into computer aided drafting (CAD) packages to configure the design and wetland volume.

### 10.2.2. Soils

The biogeochemical characteristics of soils at the site will determine their usefulness for wetland construction and planting, and will influence design, operation and performance. For example, soils with higher amounts of extractable iron and aluminium will have greater potential for P removal compared to organic soils and therefore suits for removing P from water, particularly domestic waste water or areas that received animal manure with elevated levels of P. Organic soils on the other hand will enhance sulphate reduction and are appropriate for treating acidic waters that particularly discharged from mines.

An analysis of soil from the proposed site is important to:

- determine whether the soil provides a suitable environment for plant growth and establishment;
- determine soils capacity to remove P, heavy metals and organics;
- identify soil characteristics that affect the wetland performance (water storage, erosion, soil acidity and leakage);
- establish the nature and extent of soil problems (contaminants, clay and dispersive soils); and
- determine potential input of sediment.

The number of samples and the type of analysis undertaken will depend on site complexity, size and project budget. However, a complete soil analysis and advice from a soil expert is important for soil sampling design and analytical interpretation. A range of physical and chemical tests to determine the suitability for construction and plant growth is provided below:

#### *10.2.2.1 Physical tests for construction*

- soil profile definition;
- unified Soil Classification System;
- particle size analysis;
- dispersion percentage and/or emersion aggregate test;
- shrink/swell;
- hydraulic conductivity.

#### *10.2.2.2 Chemical tests for plant growth*

The following soil tests to characterise the suitability of soil and the substrate is important for a successful wetland construction

- pH;
- electrical conductivity;
- organic matter;
- cation exchange capacity;
- trace metals;
- P sorption and fixing capacity.

*10.2.2.3 Soil profile characterization*

Soils consist of unconsolidated, natural material that supports or is capable of supporting plant life. Soils are generally divided into two different types, namely mineral and organic. Based on the amount of water present in the soil, they are further classified. Under saturated (flooded) conditions (normally in wetlands), soils are considered to be hydric. Hydric soils are ponded long enough during the growing season to develop anaerobic conditions in the upper portion. Hydric soils are developed under sufficiently wet conditions to support the presence of vegetation typical to wet areas (hydrophytic vegetation).

A soil profile consists of various soil layers described from the surface downward. These layers, called "soil horizons," are generally oriented approximately parallel to the soils surface and are characterized by their colour, structure and texture that can be seen or measured in the field. Soil horizons can be divided into major classifications called the "master horizons," designated with the letters O, A, E, B, C, and R [37]. The depth and content of these horizons varies greatly depending on the type and location of the soil. Specific information on these major horizons is provided below:

(a) The O horizon is a layer of soil dominated by organic material and layer often consists of undecomposed or partially decomposed matters such as leaf litter and other naturally occurring vegetative materials deposited on the surface of the soil.
(b) The A horizon, usually referred to as the "surface soil" or "topsoil," is a zone under the O horizon in which organic material is being added/deposited. This A horizon often has the characteristics of cultivation and related disturbances.
(c) Below the A horizon is the E layer, a mineral horizon in which the loss of silicate, clay, iron, aluminium, or a combination, has resulted in a concentration of sand and silt. The E horizon is usually darker than the B horizon located below it. The B horizon is a zone of maximum accumulation of materials from the A horizon. It is usually characterized by higher clay content and/or more pronounced soil structure development and lower organic matter than the A horizon.
(d) The C horizon which is below the B horizon consisting of unconsolidated parent material which has not been sufficiently weathered to exhibit characteristics of the B horizon. Clay content and degree of soil structure development in the C horizon are usually less than in the B horizon.
(e) The R horizon is the last major horizon and consists of the consolidated bedrock.

Because of saturation conditions of a wetland environment, soils tend to develop certain characteristics found only in wetlands. These unique characteristics result from the influence of anaerobic conditions (oxygen limiting) induced by permanent or periodic saturation. For example, anaerobic conditions result in a reducing environment, thereby lowering the reduction/oxidation (redox) potential of a soil. Anaerobic conditions result in the chemical reduction of some of the soil components, (e.g. iron and manganese) leading to the development of soil colours indicative of wetland soils. Other soil characteristics such as high organic content are also indications of a hydric soil condition.

*10.2.2.4 Soil characteristics important for wetland development*

Many soils are suitable for wetland development. Soil properties, which are considered for wetland construction, include cation exchange capacity (CEC), pH, electrical conductivity (EC), texture, and soil organic matter. These are briefly explained below:

(a) The pH of the soil affects the availability and retention of heavy metals and nutrients. The optimum soil pH is between 6.5 and 8.5.

(b) The EC of a soil affects the ability of plants and microbes to process the pollutants flowing into a wetland system. Soils with an EC of less than 4.0 dS $m^{-1}$ are best as a growth medium.
(c) The surface area of the soil particles and ‘the electrical charge on the surfaces of the soil particles account for much of a soil’s activity. Most soils carry a net negative charge, thus providing electrostatic bonding sites for positively charged ions (cations), such as $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $A1^{3+}$ and $Mn^{2+}$. These cations on the soil surface can exchange with other cations in the soil solution, hence the term cation exchange. CEC measures a soil’s capacity to hold positively charged ions and varies widely among different soils. The CEC of a soil that will be used as a planting medium should be greater than 15 cmol(+) $kg^{-1}$ soil.
(d) The redox potential of the soil is an important factor in the removal of N and P. A reducing substrate is provided to promote the removal of nitrate and ammonia. The removal of iron and manganese from mine water also requires a reducing environment.
(e) Soil’s capacity to remove and retain contaminants is a function of soil–water contact. Sandy or gravely soils have high porosity and water moves quickly through the soil. In contrast, the finer textures of silty or loamy soils promote longer soil–water contact. As a result of this fast water movement, contaminant move through fast and are not removed from the water.
(f) Soil must provide enough organic matter to fuel plant growth and microbial activity, particularly during start–up. When wetlands are built in areas with infertile soils, some fertile soil should be incorporated as substrate.
(g) Soil texture affects root growth and the retention of pollutants. Sandy, coarse–textured soils have a low potential for pollutant retention but little or no restriction on root growth. These soils hold plants well but are low in nutrients.
(h) Medium textured or loamy soils are a good choice, as these soils have high retention of pollutants and little restriction on plant growth. Loamy soils are especially good because they are soft and friable, allowing for easy rhizome and root penetration.
(i) Loamy soils also have very good water infiltration capacity that helps the wetland for ground–water recharge
(j) Dense soils, such as clays and shales, if possible are avoided, particularly at the top layer where plant is growing because they may inhibit root penetration, lack nutrients, and have low hydraulic conductivities.
(k) Soils with a high clay content aid in phosphorous retention but their low nutrient content may limit growth and development, although such soils may be suitable for wetlands used for removing P from runoff from farmlands receiving high amount of P fertilisers and animal manures.
(l) Soils with greater extractable aluminium and iron have greater potential for phosphorous assimilation than do organic soils, making them well suited for water with high levels of P.
(m) In farmland with sandy soils, it is good practice to add a mixture of loamy and clay soil to the top layer. This prevent excessive leaching at the same time provide ground–water leaching.
(n) Before incorporating soils in to wetlands chemical analysis is important. Important laboratory analysis includes clay content and type of clay, percent organic matter, and mineral contents.

*10.2.2.5 Geology and geomorphology*

A careful assessment of the underlying geology of the wetland site is useful for providing comparative estimates of earthmoving costs, ground–water flow, surface and ground–water interaction, soil fertility and land slide hazard. Several sources of geology and geomorphic information usually are available for particular site(s). This information ranges from national and regional Geological Survey maps and reports of regional geology and surficial geomorphology to detailed studies of land form assemblages. Aerial photographs and field work can also be an important source of geological information.

Understanding geomorphology from the surface down through subsurface layers to bedrock is important to determine soil layers, surface and ground–water flow dynamics, root–zone penetration areas and depths, and availability of nutrients and/or contaminants. These features provide information on plant communities which can survive on a site and are important considerations for wetland development plans if projects intend to remove or alter surface soils for levees and ditches [38].

As many wetlands in farm lands are situated within or close proximity to watercourses and also on floodplains, an understanding of the fluvial morphology is important to establish potential stability of the proposed wetland and the potential impacts of adjacent watercourse. Rock outcrops at or near the proposed wetland site or rock fragmentation on the surface enable the appraisal of the lithology and weathering status of the underlying material. This will help to assess the potential for export of materials from the catchment into the wetland.

An experienced geologist may be very useful to undertake extensive investigations related to geomorphology of the site and the surrounding area.

*10.2.2.6 Hydrology*

A primary requirement of many on–farm wetland projects is restoring and/or providing water management capabilities to a site. In order to design a wetland with enhanced performance, information is required on surface and ground–water hydrology for the wetland site. Hydrology of the site is a crucial element of the wetland design and influences the construction, operation and performance.

Information on source, timing, depth, duration, and frequency of water inputs and drainage is important. Many diverse data sets can provide this hydrological information, with the type and availability of data depending on the location and type of system.

In areas where wetlands are influenced by periodic inputs of surface water from rivers and streams, data usually are present from stream gauges along the drainages. In addition to data on water source and mass–balance water data, considerable information on water–quality surface and ground–waters for the area is also necessary.

Data on precipitation and evaporation for the proposed site and catchment is required to establish the total water balance for the wetland.

Sources of hydrological information include:

(a) local/state governments for land use data, survey information and discharge patterns and related maps;
(b) state and national water authorities for water flow records of streams and rivers;
(c) weather Departments for rainfall and evapotranspiration;
(d) establish a monitoring station if data is not available for the proposed wetland site.

The variability of inflows to a wetland affects

*10.2.2.7 Surface water–quality*

The quality of surface water near the proposed wetland development is useful for determining the water–quality objectives of the wetland. A baseline assessment of surface water–quality is important to identify existing water–quality problems such as excess nutrient (N and P), heavy metals, organic pollutants, pH (acid mine drainage) and salinity. More detailed information is provided under monitoring (Section 16).

Base line water–quality data is available from local, state and national government records. Many academic and research organisation have also developed computer based simulation models to estimate water–quality and quantity for existing and future land uses which can be used gather baseline information. The modelling information can be calibrated with field measured data and can be used to design the wetland.

*10.2.2.8 Ground–water and hydrogeology*

Wetlands with a hydrological connection to ground–water can play a role in maintaining water supplies by: (1) recharging ground–water supplies: water stored in wetlands will slowly percolate into the underlying aquifer, and (2) discharging ground–water: water flows from the ground–water system to surface water bodies including the wetland itself, rivers and streams during dry periods.

Because of recharge and discharge there is opportunity for contaminants to be transported between wetlands and ground–water that will depend on:

(a) quality of water entering the wetland and the capacity of the wetland to remove/assimilate pollutants;
(b) quality of ground–water relative to the wetland;
(c) pollutant and hydraulic loading to the wetland;
(d) potential ground–water recharge and discharge areas;
(e) geology and characteristics of soils;
(f) vulnerability of ground–water to contamination;
(g) current uses of ground–water and the surface water.

Available information on ground–water characteristics can be use. In the case if information is not available bores can be drilled in the area. The following information is useful.

(a) depth, volume and yield of aquifer;
(b) ground–water–level fluctuation (from rainy season to dry season and extraction periods);
(c) areas of ground–water recharge and discharge areas;
(d) ground–water–quality;
(e) hydraulic conductivity of soils;
(f) current and potential uses of ground–water;
(g) ground–water flow direction and its rate;
(h) ground–water gradient and pressure levels;
(i) location of ground–water bores available in the area.

*10.2.2.9 Climate*

As a shallow water body, wetland functions are influenced by climate and weather. Temperature variations impact the performance of wetlands by altering the physical and biological activities in the wetland system. The main reasons for temperature effect on wetland functions are (1) temperature modifies the rates of several key biological processes, (2) temperature is sometimes a regulated water–quality parameter, and (3) water temperature is a prime determinant of evaporative water loss processes. Therefore weather patterns and climate regimes can restrict the form a wetland may take, dictate its biological component, operating procedures and the performance.

The climate of a location influence the wetting and drying cycles, the occurrence of insect pests and the incidence and rate of soil erosion. Climate and weather patterns will determine the length of the growing season and influence the type biological systems present in the wetland leading performance. It also influences the flow and water column depth, favour weed growth and kill the biota of the wetland. Pollutant concentrations will increase during summer at the same time rainfall decreases the concentration of pollutants entering the wetland.

Useful climate data important for wetland include (1) rainfall and potential evaporation, and (2) temperature which will influence plant selection and time of year to plant. Most of the climate data will be obtained from national weather (Meteorology) office.

## 10.3. DESIGN CONSIDERATIONS FOR WETLAND DEVELOPMENT

Despite a large amount of research and published information, the design of wetlands in a farmland for applications such as the capture, storage and the removal of chemicals and contaminants in water have not yet been determined. Many wetland systems in agricultural landscapes have not been adequately monitored or have not been operating long enough to provide sufficient data for analysis. Among the systems that have been monitored, performance has varied and the influences of diverse number of factors that affect performance, such as location, type of water, wetland design, climate, weather, disturbance, and daily or seasonal variability have been difficult to quantify.

The general guidelines for creating successful wetland in farmlands are:

(a) Keep the design simple such as minimal maintenance, use of natural energy (gravity flow) and capable of withholding extreme weather events (storms, floods, and droughts).
(b) Design the wetland with the landscape, not against it. Integrate the design with the natural topography of the site. Avoid over–engineering the design with rectangular basins, rigid structures and channels, and regular morphology.
(c) Design the system for function, not form. For instance, if initial plantings fail, but the overall function of the wetland, based on initial objectives, is intact, then the system has not failed.
(d) Give the wetland system time. Wetlands do not necessarily become functional overnight and several years may elapse before performance reaches optimal levels.

### 10.3.1. Wetland designers

Although wetlands are simple to engineer, they are ecologically complex and their design requires a wide range of expertise. The ideal designer/engineer needs to consider the following when designing a perfect wetland to meet its objectives

(a) physical, chemical and biological processes and the ecological interaction with the environment,
(b) engineering techniques (soil and water engineering, hydrology etc.),
(c) soil's relationship with wetland process;
(d) ground–water dynamics, planting procedures, water–quality assessment, monitoring, landscape planning and aquatic habitats.

A team with multidisciplinary skills is important and is advocated for wetland design. The quality of wetland (the performance to satisfy design objectives) is reliant on the skills and experience of the designer(s).

*10.3.1.1 Concept development*

Planning and developing preliminary design for the wetland based on the need is defined as concept development. This is the preliminary step for the large–scale project where it can be used to provide estimates of the project budget which include land acquisition and cost of feasibility. In the concept phase all tasks that are supposed to be included in the wetland construction project are defined but the details of each task is much lower than that in the main project. The important tasks to be considered during the concept design include:

(a) Set initial objective for the wetland.
(b) Identify potential constraints by undertaking preliminary site and catchment investigation.
(c) Examine opportunities within the identified constraints.
(d) Develop preliminary design.

The concept design helps to develop a feasible wetland proposal should meet the project objectives and lead to the development of preliminary design.

*10.3.1.2 Preliminary concept design*

Preliminary design consists of a configuration and overall size for the wetland. Depending on the project objectives, the wetland configuration and different components can be incorporated. The individual components can be reduced depending upon the constraints of the project.

Small wetland construction projects require less detail and typical configurations can be adapted to sites taking into account project constraints. For larger projects typical configurations need to be significantly modified or new configurations to be developed.

At the end of preliminary design an option for wetland construction can be presented as a concept plan, and the sophistication of the plan match the budget and scale of the project. The plan should include relevant information on wetland configuration, approximate size and known constraints such as soil characteristics.

The preliminary concept design can be used to (1) convey information to the public about the project, (2) provide preliminary information to the project design team, and (3) provide information for funding proposal and budget development.

## 11. DETAILED CONCEPT DESIGN

The detailed concept design phase is developed from the preliminary design phase. This phase has sufficient design standards that help to obtain approvals, prepare document relevant to environmental clearances and establishing wetland components. Any modification to the design can be carried out during this phase of design development. Most important considerations given during this phase is configuration and sizing the wetland system which are briefly provided below:

### 11.1. WETLAND ZONE CONFIGURATION

Proper wetland configuration is important to provide efficiency and minimum maintenance, avoiding bad odour, insect and clogging amongst others. This may be refer to zone configuration in which the wetland can be divided into zones such as inlet, deep water, plant and outlet depending on the type of wetland. Within this also include gross pollutant traps and sedimentation basin.

For wetlands in agricultural catchments sediment basins are important for removing sediment originating from agricultural land. Any wetland development needs to look at the importance of having gross pollutant traps and sediment basins for improving the performance, aesthetic values of wetlands in agricultural catchments and to meet water–quality objectives. The surface area and depth of sedimentation basin would depend on the runoff generated in the catchment.

For each of the zones there are components and each component has a specific function (Table 2).

TABLE 2. SUMMARY OF WETLAND ZONES, COMPONENTS AND THEIR FUNCTIONS (DLWC 1997)

| Zone | Components | Functions |
|---|---|---|
| Inlet zone | Gross pollutant traps | Remove larger pollutants such as plastics, papers and other wastes |
| Deep water zone | Sedimentation basins (open water) | Remove sediments and coarser soil particles |
| | Water plants | Bed protection and water–quality |
| Plant zone | Reed beds | Water–quality and habitat |
| | Flow diversion | Reduce potential for bypass and improve water–quality |
| Outlet zone | Weirs, spillways and water–level control | Easy monitoring, water–level control and flow management |

The performance of a wetland depends upon the ratio of the open water to the plant are. For example, the water–quality performance increased as the open water to plant area increased (Fig 5). So it is important to have a larger planting area compared to the open water area.

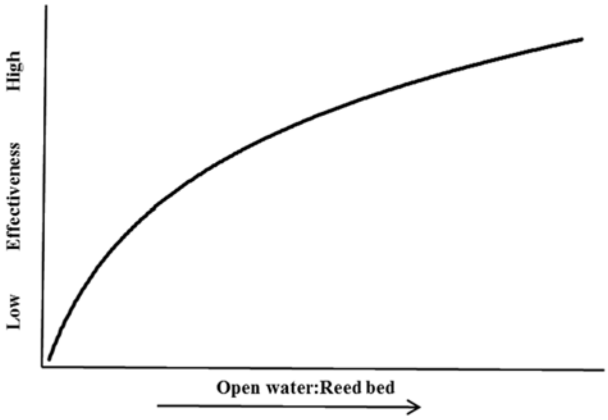



*FIG. 6. Effectiveness of water–quality objectives for different open water and reed bed ratios.*

## 11.2. HYDRAULIC CONFIGURATION

The two main objectives of wetland development in agricultural catchments are (1) capture and store water, and (2) remove nutrient and pollutants. Before any wetland design process can begin, the catchment and the water to be put through the wetland is evaluated. One of the most critical aspects of a wetland design is the proper estimation of water volumes generated in the agricultural catchment.

The volume of water (daily/weekly/monthly) generated in the catchment need be determined for all water sources during different periods of the year. Wet weather periods may provide the greatest volume of water; however the pollutant concentration may be less than during dry summer months (dilution factor). In addition to the volume of water one additional important factor in designing a wetland in agricultural catchment is the concentration of nutrients and other pollutants which determines the maximum load of these pollutants [39].

The size of wetlands and the selection soil and plant to be used in the wetland depend on the volume of water generated in the catchment and the nutrient and pollutants it carries to the wetland. Daily flows ($m^3$) times the concentration of a specific pollutant (mg $L^{-1}$) provides an estimate of the mass of pollutant (kg $day^{-1}$) requiring removal in the wetland that can be used to estimate the size of the wetland.

Hydraulic configurations are established based on some preliminary calculations and system sizing. The preliminary calculation involves establishing catchment runoff and average depth. The system sizing is used to establish the area required for establishing the wetland.

### 11.2.1. Catchment runoff

Estimation of daily runoff ($RO_d$) is required for estimating the overall size of the wetland and sizing the planting zone. The $RO_d$ is calculated by dividing the average annual yield (ANY) of the catchment by 365:

$$RO_d = \frac{ANY}{365} \tag{8}$$

Once the $RO_d$ is estimated, the average depth (AD) needs to be estimated for sizing the wetland system and sizing the planting area. Normally the AD increased as volume of open water divided by volume of water in the planting area increased. However, if the planting area is increased relative to open water area then the average depth can be decreased. So the water column depth for a wetland can be adjusted depending on the areas of the open water and the planting zone.

### 11.2.2. Sizing of wetland

The surface area of the catchment also is very useful to size the wetland area (catchment area method). It should be noted that the required wetland area be >2% of the catchment area. This is based on information collected in USA that those wetlands that are >2% performed better in meeting the water–quality objectives compared to those with <2%. The variability in the catchment such as land use, water–quality, topography and soils may also affect the performance. In addition, the peak water flow and pollutant loadings may also influence the performance, even failure of the system.

The wetland sizing will also be determined using actual performance of existing wetlands (generic curve method). However, this may overestimate the required area due to different configuration of the existing wetlands that have been used for performance assessment. The curve method uses the following approach:

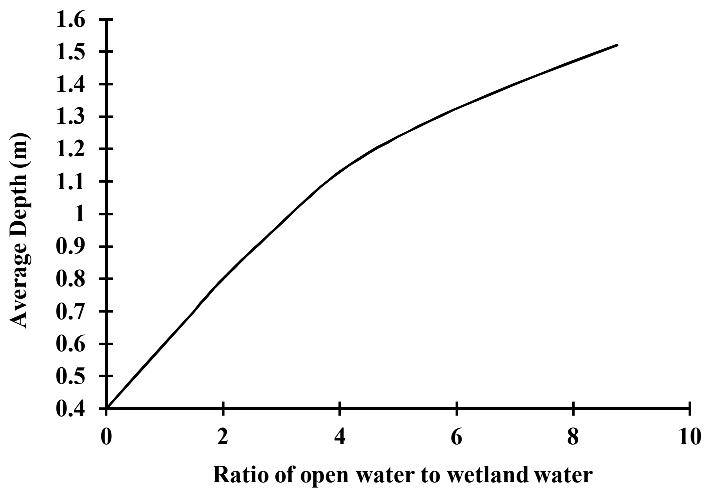
(a) Determine the removal rate required (%).
(b) Determine the hydraulic residence time (HRT).
(c) Calculate the volume of the wetland:

$$Wetland\ Volume\ (m^3) = RO_d\ (m^3/day) \times HRT\ (day) \quad (9)$$

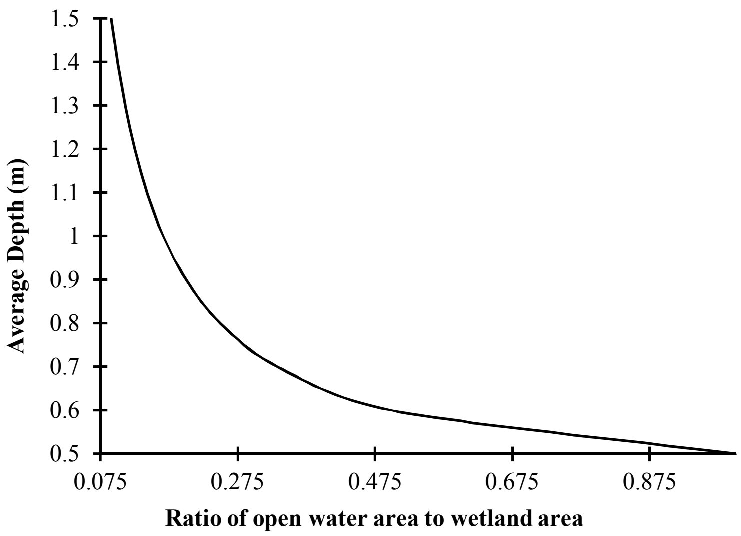
(d) Calculate area of wetland:

$$Wetland\ Area\ (m^2) = Wetland\ Volume\ (m^3)/AD(m) \quad (10)$$

where the AD is determined from the curve of AD versus the volume the ratio of open water to reed bed (Fig. 6).




(a) Wetland sizing based on average depth and the water volume ratios




(b) Wetland sizing based on average depth and the area ratios

*FIG. 7. Estimation of average depth for wetland development based on volume and surface area of open water and planted area.*

The overall size of the wetland is equal to the sum of the sizes of the open water and the planting area. Key information required for sizing the two components are:

(a) sedimentation in the open water to separate suspended particles from the runoff water and an understanding of long term sediment accumulation is important.
(b) planting area size (the main wetland) depends on wetland objectives, available land area, runoff flow rates and frequency of flow.

The planting area provides many of the biogeochemical processes and the performance of this zone is critical. Maximising HRT allows various wetland processes to improve the water–quality. Periods of no flow and base flow to the wetland should be considered for sizing the wetland. If base flow is lower than water losses (evapotranspiration and seepage etc.), the size of the wetland can be reduced to ensure the wetland is inundated with water. Maintaining an appropriate water column depth in the planting area is important to manage the wetland during base flow period.

Shallow wetland provides benefits to wildlife (habitat) and pollution control (removing nutrient, sediment and organic contaminants) by increasing the surface area. So it is always recommended that maximising the area of the wetland (the planting area) provides maximum benefits.

In wetland systems built with large increases in depth instead of surface area to control peak flows, the system will contribute less to meet water–quality. On the other hand wetlands with large surface area and shallow depth contribute significantly for water–quality improvements. An example of a system design for wetland development is provided in the table below.

EXAMPLE OF DESIGNING A WETLAND IN AN AGRICULTURAL CATCHMENT

*Scenario*

The farm wetland is to be located in an agricultural catchment of 250 ha. Cropping occupies about 70 of the catchment and the remaining with pasture and rangeland. Approximately six ha of land is available for wetland construction. The average annual rainfall for the catchment is 650 mm with 120 rainy days per year. The wetland has the primary objective of capturing water and removes sediment, N and P from the water before it reaches the downstream reservoir.

Based on the water balance about 20% of rainfall converted to runoff which is equal to 325,000 $m^3$ per annum.

Preliminary calculations – Catchment runoff:

Daily runoff ($m^3$) = Annual yield ($m^3$)/365 (runoff days) = 325,000/365 = 890.4 $m^3$/day

Average depths:

There are two methods available for estimating the average depth of the wetland to be designed.

In the absence of any data it is assumed that the ratio of the volume of open water to the planted area as 2:1. The average depth related to this ratio is 0.78 meter. This was selected based on the objective of the wetland which is mainly to capture water and to a less extent nutrient removal.

The modified mean annual runoff method provided an average depth value of 0.7 m.

Both the above approaches use the relationship between average depth and volume ratios (Fig. 6).

System Sizing:

The area available for developing wetland is 6 ha which is >2% and indicates the site is feasible for wetland development.

For an hydraulic retention time of 15 days, the size of the wetland area is estimated based on the following calculation:

$$Daily\ runoff\ (m^3) = \frac{15}{Average\ depth\ (m)} \tag{11}$$

$$890.4\ m^3 = \frac{15}{0.78\ (m)} = 1.71\ ha \tag{12}$$

Open water sizing

The surface area required for open water is calculated using the following equation:

$$A_s = \frac{Q}{e_r x w} \tag{13}$$

$A_s$= Open water surface area, Q=design flow rate for the sedimentation pond, $e_r$=efficiency expressed in decimals, and w=settling velocity of sediments. Theoretical settling velocities and sedimentation efficiencies are provided in Table 4 below.

Assuming an average sediment particle size of 0.05 mm and a settling velocity of 0.0019m/s the surface area ($A_s$) is 0.65 ha. The dimensions of the open water are based on the surface area of the open water and the basis of the calculations are provided below:

$$Width \ \leq \sqrt{\frac{A_s}{3}} = 46.5\ m \tag{13}$$

$$Length \ \geq 3 \times \sqrt{\frac{A_s}{3}} = 139\ m \tag{15}$$

Therefore the open water dimensions are 46.5m by 139 m.

TABLE 3. SETTLING VELOCITIES AND SEDIMENTATION EFFICIENCIES FOR SOIL PARTICLES WITH DIFFERENT PARTICLE SIZE

| Particle Size (mm) | Settling Velocity (m/s) | Specific Weight | Sedimentation Efficiency (%) |
|---|---|---|---|
| 0.500 | 0.058 | 2.65 | 100 |
| 0.200 | 0.020 | 2.63 | 95 |
| 0.100 | 0.007 | 2.54 | 84 |
| 0.050 | 0.0019 | 2.41 | 76 |
| 0.020 | 0.00029 | 2.0 | 60 |
| 0.010 | 0.000073 | 1.8 | 50 |
| 0.005 | 0.000018 | 1.7 | 44 |

### 11.2.3. Design of farm wetlands

Wetlands in farm areas need to fit for reliable capture, storage and efficient treatment of water and the associated nutrients, particularly N and P. They vary in size, design and location that determine the design of such wetlands. These wetlands should perform well especially during

storm events that generate high volumes of water from the farm catchment. As these wetlands are important for water conservation, they need to be practical in their design to maximise the storage of water. In addition, they need to be relatively simple to build, economically and environmentally sustainable to operate and maintain, and safe to farmers and to the general public.
Important issues to be considered during the design of a wetland in agricultural farmlands include:

(a) location of the dam and its minimal dimensions;
(b) broader catchment land uses and its impact on the wetland;
(c) vegetation already found within the wetlands and the potential for the presence of weeds;
(d) cost of installation;
(e) suitability of the soil;
(f) hydrology.

## 12. CONSTRUCTION

Despite a large number of research and published information on wetland design and construction, it is difficult to accurately design a wetland for different applications. Many wetland systems developed in farmlands have not been adequately monitored or have not been operating long enough to provide sufficient data for analysis and to assess the performance. Among the wetland systems that have been monitored, performance has varied and the influences of many factors that affect performance, such as location, type of water or runoff, wetland design, climate, weather, disturbance, and daily or seasonal variability, have been difficult to quantify.

In general, wetland construction involves three stages that include (1) construction planning and management, (2) vegetation establishment, and (3) erosion and sediment control measures.

The construction planning and management will help for smooth start for the construction. Apply for a local permit as early as possible can help prevent delays for the construction. Planning for vegetation management is key part of this planning. The specifics of construction for the wetland project need to be documented as a guidance that includes design, construction guidelines, existing infrastructure, required construction materials, equipment required, and sequences of task. The contractors and contract processes need to be identified during this stage.

The construction management plan is followed by construction techniques that include (1) site preparation, (2) planting preparation, (3) site restoration, (4) soil preparation, its placement and compaction and (5) establishing structures.

Once the land is identified, it is cleared and the site is prepared by removing the existing vegetation. The top soil is removed and stockpiled nearby so that it can be used as a top layer for the wetland vegetation. Generally mid spring to early summer is ideal for constructing wetlands as plants can be established easily during this period. The specific details of construction are written as simple guidelines and need to be provided to potential contractors and people involved in construction.

It is important to have onsite meetings with the contractors and construction people. Thorough communications on site goals will help to set standards for successful wetland construction on time with allocated budget.

The number of plants required for the wetland depends on the surface area and the plant spacing. It is always advised to have plant spacing of 30 cm (12 inch) which normally gives full surface coverage within one year of plating. If the spacing is increased to 60 and 90 cm then the full surface coverage will be achieved in two and three years. Full surface coverage by plant within the first year helps to remove pollutants better than second and third year coverage.

The wetland construction sequence involves (1) site layout, (2) erosion control measures, (3) establish outlet, (4) excavation and soil preparation, (5) wetland bank stabilisation, (6) stabilisation of wetland inlet, (7) wetland surface preparation, (8) planting and (9) water management. A detailed approach is important for each of the sequence.

## 13. WETLAND MANAGEMENT

Management of wetlands generally consists of four tasks namely monitoring, operation, inspection and maintenance. (1) Monitoring involves water–quality, vegetation, organisms and habitat, (2) Operation mainly looks at controlling water–level, (3) inspections carried out for wetland structure and embankment management, and (4) maintenance involves repairing damages to structures and control of weed.

For the farm wetland to perform well, an effective post construction management plan is important. This management plan includes operation, maintenance and monitoring and focus on the most important factors that influence the performance or efficiency of wetlands. These include:

(a) providing opportunities for establishing sufficient contact between water and the microbial community, soil and the litter component;
(b) ensuring that water reach all parts of the wetland;
(c) creating an environment which is health for microbial organisms;
(d) establishing healthy vegetation in the wetland.

An operation plan ensures that the wetland operates as designed and monitoring ensures that the design objectives are met. In addition, the performance of the wetland is monitored continuously. Management of wetland in agricultural farms generally consists of four tasks that include: (1) operation (water flow adjustments including water column depth), (2) maintenance (repair damages and removing weeds and gross pollutants), and (3) monitoring (water–quality, habitat, flora, fauna and regular site inspection).

## 14. OPERATION AND MAINTENANCE

The details of post construction operation and maintenance (OM) of wetland are written in OM plan developed during the wetland design. This plan can be updated based on lessons learned from the operation of the wetland. As the OM is a long term strategy, the plan identify clearly those who are responsible and those who are paying for the OM. The plan generally addresses the following:

(a) controlling water depth;
(b) scheduling for cleaning and maintaining inlet, outlet and the entire wetland;
(c) monitoring sediment accumulation and depth of sediment;
(d) monitoring depth of sediment accumulation before removal is required;
(e) managing continuous flow to the wetland avoiding flow surges;
(f) scheduling recharge and discharge in the wetland.

Key aspects that are part of operation and maintenance are (1) hydrology, (2) wetland structures, (3) vegetation, (4) animals, and (5) mosquitoes.

A legally binding agreement between the wetland management team and the local authority reviewing the OM. Typical inspection and maintenance item and the frequency are provided in Table 5. Regular monitoring of other failures is also important.

TABLE 4. GENERAL INSPECTION AND MANAGEMENT FOR WETLAND FUNCTIONALITY

| Inspection Items | Maintenance Items | Frequency |
|---|---|---|
| Routine inspection of damage to the structure, pipes and channels and sediment deposition | Repair and maintenance of the damaged structure and removal of sediment when needed | Between one three years |
| Inspection of vegetation growth (ensure at least 50% plant survive), invasive plants and floating debris | Replant wetland vegetation | Between one year and 18 months<br>After big storm events |
| Monitor sediment deposition in wetland and the forbay | Forbay maintenance and sediment removal when necessary | Two to seven years when required |

## 15. MONITORING

Monitoring is an integral part of wetland management as it provides data and information for (1) improving effectiveness of the wetland, (2) identifying failures and other problems at the earliest possible, (3) identifying and documenting potentially toxic substances before they bio accumulate in the system, and (4) ensuring compliance with regulatory requirements. Monitoring also helps for its input to research activities.

Monitoring is important to measure whether the wetland meets its objectives. It identifies problem early when intervention is most effective. The level and extent of monitoring the wetland depends on the objective and complexities of the wetland system. Normally it takes some time to know the performance of the system. Changes to the performance of the wetland become clearer as the system matures. Information obtained from monitoring helps to revise update management strategies for the wetland system that will reduce cost over longer period. The monitoring plan for the wetland system will need to be carefully and methodologically so that information that is more important are collected and interpreted.

### 15.1. MONITORING PLAN

Monitoring of wetland functions helps us to assess the performance of a particular wetland to meet the objectives and to develop strategies to improve the performance if required. It also helps to identify problems early and implement remedial measures to improve performance of under–performing wetland systems and provide data that can be used for research interpretation and improving treatment performance. A written monitoring plan that include (1) clearly stated objectives of the wetland system, (2) the specific objectives of the monitoring programme, (3) responsibilities on who is doing what (both institutional and technical), (4) approach, (5) activities, tasks and inputs, (6) data management, (7) resource requirements, (8) and reporting is important for a successful monitoring programme

Monitoring is required for two purposes which are (1) discharge compliance requirement, and (2) managing system performance.

When a farm wetland is designed to manage water–quality and quantity downstream the discharge volume and water–quality need to be monitored that comply with discharge.

For system performance the following monitoring the following parameters are important.

(a) Inflow and outflow volumes of water;
(b) Water–quality change between inflow and outflow.

In farm wetland, monitoring contaminants is important in addition to water quantity as the water can be used for livestock consumption and irrigation. These contaminants include (1) N, (2) P, (3) total suspended solids, (4) heavy metals, (5) bacteria.

### 15.1.1. Wetland inspections and checklists

Inspections are required to verify that all components of wetlands are functioning properly. Such inspections will provide information on what to be monitored at regular intervals. The inspection checklist mainly includes (1) the inlet zone, (2) deep water zone, and (3) macrophyte zone. At the inlet zone the structure, sediment build–up and trash and debris are common checklists. In deep water zone any bank erosion along with sediment build–up and trash and debris need be checked. At the macrophyte zone bank erosion, development of weeds, plant health and the condition of structures need to be checked. Once the check list is completed then the plan needs to be developed on the time interval for removing gross pollutants and repairing the damages to the inside of the wetland.

### 15.1.2. Monitoring for surface water–quality

Majority of wetlands in agricultural landscapes have main two functions namely to (1) provide water for irrigation, and (2) improve water–quality downstream. Both of these functions required very good water treatment in the wetland. Improvement in water–quality of wetlands can easily be assessed by monitoring a range of water–quality parameters at both the inlet and outlet of the wetland. Relevant water–quality indicators are selected for regulatory compliance and operational controls.

For pollutant such sediment and nutrients monitoring, actual performance can only be evaluated based on pollutant loads rather than concentrations as they are misleading. For estimating loads (Table 6), measurements on flows into and out of wetland are required. These measurements can be carried out daily over a period of 7 to 10 days which can be repeated depending on the weather. Such monitoring reduces measurement variabilities in inflows and outflows. Automatic flow measurement devices are available commercially and they can be even monitored remotely using online systems. Flows can also be measured installing appropriate weirs and gauges.

For assessing water–quality performance it is recommended to sample water in the wetland and also measure the water–quality parameters of inflow and outflow. Water samples can also be collected using automatic samplers which are commercially available. In some wetlands, which are large in surface area, the pollutants are removed in the first part of the wetland, however, they re–suspend in the downstream area of the wetland. So it is important to sample water along the wetland which can give good indication of the whole wetland performance.

The establishment of a suitable database for the storage and retrieval of information is important for water–quality monitoring.

### *15.1.2.1 Estimating pollutant load for wetland*

The amount of pollutant entering a wetland is estimated by using both the flow data and the concentrations of pollutants in the water. Concentrations of pollutants are measured by physical or chemical water–quality tests. Concentrations when combined with flow data give the amount of pollutant over a particular period of time and is provided below:

$$\textit{Load} = \textit{Flow (water vol. per time unit)} \times \textit{Concentration (weight per vol. unit)} \quad (16)$$

$$\textit{Flow} = \textit{Velocity} \ (m\ s^{-1}) \times \textit{Cross sectional area of stream} \ (m^2) \quad (17)$$

The concentration of the pollutants entering the wetlands provides little information on pollutant retention. In some wetland systems, the concentration of pollutants in the outflow are often higher that of inflow. This may be due to water loss from the wetland by evapotranspiration leading to increased concentrations. The amount of pollutants entering and leaving wetlands is a good indicator of wetland performance.

Estimating pollutant load to wetlands under different circumstances can also provide some good picture of pollutant transport and transformation within the wetland.

### **15.1.3. Ground–water interaction and transformation**

As a component of hydrological cycle, ground–water interact with wetlands and hold and store water that support ecosystem functioning. Ground–water interact with wetland in three ways such as:

- ground–water flow to the wetland;
- water loss from the lake to the ground–water (saturated zone);
- ground–water inflow in some parts and seepage loss in other parts of wetland (flow through wetlands).

The interaction between ground–water and the wetland may need to be monitored to determine the effect of ground–water on wetland and vice versa. Losses from the wetland to ground–water can be assessed through water balance of wetlands considering all inputs and outputs including evapotranspiration. The use of 2H and 18O isotopes can help validate evapotranspiration measurements [40]. In addition, installation of piezometers or ground–water bores helps measure ground–water depth adjacent to wetlands. Continuous losses from wetland to ground–water affect the performance of wetlands and required remedial actions.

Ground–water quality is monitored by bore sampling located at both upstream and downstream and also up and down slope of the wetland. The data can be used to indicate changes occurring within the wetland and also the ground–water and their interaction.

## REFERENCES


[1] HAMADA, H., Technologies for harvest and effective use of water in rainfed agricultural areas, Japan Agric. Res. Quarterly **40** (3) (2006) 217–223.

[2] GOLDMAN, M.A., NEEDELMAN, B.A., Wetland restoration and creation for nitrogen removal: Challenges to developing a watershed–scale approach in the Chesapeake Bay coastal plain, Adv. Agron (2015) 132–138.

[3] BOERS, T.M., BEN–ASHER, J., Review of rainwater harvesting, Agric. Wat. Manage **5** (1982) 145–158.

[4] OECD, Sustainable Use of Wetlands: DAC Guidelines on Aid and Environment, OECD (1991) P 67.

[5] MITSCH, W. J., GOSSELINK, J. G., Wetlands (2007), John Wiley & Sons.

[6] MCCARTNEY, M.P., et al., Working wetlands: Classifying wetland potential for agriculture, Research Report **90 (**2005), International Water Management Institute (IWMI), Colombo, Sri Lanka.

[7] REED, S.C., et al., Natural Systems for Waste Management and Treatment, McGraw–Hill Inc., New York (1988).

[8] REED, S.C., et al., Natural Systems for Waste Management and Treatment. 2nd Edition, McGraw–Hill Inc., New York (1995).

[9] USEPA, Design Manual. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment, 625/1–88/022 (1988) P.83, USEPA, Washington D.C.

[10] HAMMER, D.A., “Constructed Wetlands for Wastewater Treatment – Municipal, Industrial and Agricultural”, Proc. of the First International Conference on Constructed Wetlands for Wastewater Treatment, Chattanooga, USA, Lewis Publishers Inc., Michigan (1989).

[11] COOPER, P.F., FINDLATER, B.C., Constructed Wetland in Water Pollution Control. In proceedings of the International Conference on the use of Constructed Wetlands in Water Pollution Control, Cambridge, United Kingdom, Pergamon Press, Oxford (1990).

[12] MOSHIRI, G.A., Constructed Wetlands for Water–quality Improvement, Lewis Publishers, London (1993).

[13] KADLEC, R.H., KNIGHT, R.L., Treatment Wetlands, Lewis Publishers, New York (1996).

[14] DLWC, The Constructed Wetlands Manual, Department of Land and Water Conservation, NSW, Australia (1997).

[15] CARTER, V., Technical Aspects of Wetlands: Wetland Hydrology, Water Quality and Associated Functions, United States Geological Survey (1996) Water Supply Paper 2425.

[16] FRETWELL, J.D., et al., National Water Summary: Wetland Resources, United States Geological Survey, 409 National Center, Reston VA 22092, USA(1996).

[17] CARTER, V., An overview of hydrologic concerns related to wetlands in the United States, Canadian J. Botany **64 (**1986) (2) 364–374.

[18] NSW ENVIRONMENTAL PROTECTION AUTHORITY, Wetlands for Treating Wastewater, NSW EPA, Sydney, Australia (1995).

[19] MCCLAIN, M.E., et al., Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems, Ecosystems **6 (**2003) 301–312.

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, The Application of Isotopic Techniques to the Assessment of Aquifer Systems in Major Urban Areas, IAEA-TECDOC-1298, IAEA, Vienna (2002).

[21] FAULKNER, S.P., RICHARDSON, C.J., Physical and Chemical Characteristics of freshwater Wetland Soils. In Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agriculture (HAMMER, D.A., Ed.), Lewis Publishing, (1989) 41–72.

[22] DURAND, P., Nitrogen Processes in Aquatic Ecosystems. The European Nitrogen Assessment, (SUTTON, M.A., HOWARD, C.M., ERISMAN, J.W., BILLEN, G., BLEEKER, A., GRENNFELT, P., VAN GRINSVEN, H., GRIZZETTI, B., Eds.), Cambridge University Press (2011) 126–146.

[23] BRODERICK, S.J., et al., Denitrification in a natural wetland receiving secondary treated effluent, Water Resources **22** 4 (1988) 431–439.

[24] JOHNSTON, C.A., et al., The cumulative effect of wetlands on stream water–quality and quantity: A landscape approach Biogeochemistry **10 (**1990) 105–141.

[25] PINAY, G., et al., Topographic influence on carbon and nitrogen dynamics in riverine woods Archiv für Hydrobiologie **114** (1989) 404–414.

[26] SABATER, S., et al., Nitrogen removal by riparian buffers along a European climatic gradient: Patterns and factors of variation Ecosystems **6 (**2003) 20–30.

[27] HAAG, D., KAUPENJOHANN, M., Landscape fate of nitrate fluxes and emissions in Central Europe: A critical review of concepts, data and models for transport and retention Agric. Ecosys. Environ. **86** (2001) 1–21.

[28] SKOULIKIDIS, N., AMAXIDIS, Y., Origin and dynamics of dissolved and particulate nutrients in a minimally disturbed Mediterranean river with intermittent flow J. Hydrol. **373** (2009) 218–229.

[29] MENGIS, M., et al., Multiple geochemical and isotopic approaches for assessing groundwater nitrate elimination in a riparian zone Groundwater **37 (**1999) 448–457.

[30] PINAY, G., et al., Importance of Near and In–stream Zones in Small Agricultural Catchments to Buffer Diffuse Nitrogen Pollution, Proceedings of the International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. (HENG, L.K., SAKADEVAN, K., DERCON G., NGUYEN M.L., Eds), Food and Agricultural Organization of the United Nations (2014) 179–183.

[31] CLÉMENT, J.C., et al., Isotopic investigation of denitrification in a riparian ecosystem in Western France J. Appl. Ecol. **40** (2003) 1035–1048.

[32] WELL, R., et al., Are dual isotope and isotopomer ratios of N2O. Useful indicators for N2O turnover during denitrification in nitrate–contaminated aquifers? Geochimica et Cosmochimica Acta **90** (2012) 265–282.

[33] KADLEC, R.H., Phosphorus removal in emergent free surface wetlands. J. Environ Sci. Health, Part A: Toxic/Hazardous Substances and Environmental Engineering. **40 (**2005) (6–7) 1293–1306.

[34] HYLAND, C., et al., Phosphorus Basics-The Phosphorus Cycle. Fact Sheet 12, Agronomy Fact Sheet Series Cornell University Cooperative Extension (2005).

[35] REDDY, K.R., et al., Phosphorus Retention in Streams and Wetlands: A Review (1999).

[36] USACE, Guidance on Compensatory Mitigation Projects for Aquatic Resource Impacts Under the Corps Regulatory Program Pursuant to Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899, Regulatory Guidance Letter (2002) 02–2.

[37] ITRC (Interstate Technology & Regulatory Council), Characterisation, Design, Construction, and Monitoring of Mitigation Wetlands, WTLND–2, Washington, D.C.: Interstate Technology & Regulatory Council, Mitigation Wetlands Team (2005).

[38] HEITMEYER, M.E., et al., Wetland Design and Development. In J.T. Anderson and C.A. Davis (eds.), Wetland Techniques: Volume 3 (2013): Applications and Management, US Fish & Wildlife Publications, Paper 443.

[39] TOUSIGNANT, E., et al., Guidance Manual for the Design, Construction and Operations of Constructed Wetlands for Rural Applications in Ontario (1999) 164.
[40] JASECHKO, S., et al., Terrestrial water fluxes dominated by transpiration, Nature **496** **(**2013) 347–350.
[41] MUCCIO, Z., JACKSON, G.P., Isotope ratio mass spectrometry, Analyst **134** (2009) 213–222.
[42] WU, T., et al., Measurement of the D/H, $^{18}O/^{16}O$, and $^{17}O/^{16}O$ isotope ratios in water by laser absorption spectroscopy at 2.73 µm, Sensors **14** 5 **(**2014) 9027–9045.
[43] BOWEN, G.J., 2010. Isoscapes: spatial pattern in isotopic biogeochemistry, Annual Rev. Earth and Planetary Sci. **38** 1 (2010) 161–187.
[44] WASSENAAR, L. I., et al., Isotope hydrology of precipitation, surface and groundwaters in the Okanagan Valley, British Columbia, Canada, Journal of Hydrology **411** **(**2011) 37–48.
[45] CRAIG, H., Isotope variations in meteoric waters, Science **133** **(**1961) 1702–1703.
[46] LIU, X.T., MA, X.H., Natural Environmental Changes and Ecological Protection in Sanjiang Plain, Science Press, Beijing (2002) (in Chinese).

## ANNEX I: ISOTOPIC SIGNATURES OF HYDROGEN ($^2$H), OXYGEN ($^{18}$O) AND N ($^{15}$N)

The use of a number stable isotopes such as hydrogen–2 ($^2$H), oxygen–18 ($^{18}$O) and nitrogen–15 ($^{15}$N) to assess water and nutrient dynamics help to configure and identify ideal locations for developing wetlands in agricultural landscapes and its management. The concept of isotopic signature ($\delta^2$H, $\delta^{18}$O and $\delta^{15}$N) is important for assessing water and nutrient dynamics in wetlands and is given by the following equation

$$\delta_{sample} = \frac{[R_{sample} - R_{standard}]}{R_{standard}} \times 1000 \qquad \text{(I-1)}$$

where $R_{\text{sample}}$ and $R_{\text{standard}}$ are isotopic ratios of sample (e.g. water of the wetland) and standard (Vienna Standard Mean Ocean Water).

The $\delta^2$H, $\delta^{18}$O and $\delta^{15}$N of water samples are determined by using (1) isotopic ratio mass spectrophotometry (IRMS) and/or (2) cavity ring down spectroscopy (CRDS). A detailed description can be found in the literature (e.g. [41, 42]. Isotopic signatures $\delta^2$H and $\delta^{18}$O are useful to identify sources of water in a wetland. Similarly, $\delta^{15}$N is useful for quantifying N removal and biological denitrification in wetlands, particularly quantifying both nitrous oxide ($N_2O$) and N gas ($N_2$).

### THE CONCEPT OF DEUTERIUM EXCESS

Any interpretation of isotopic signatures (δ) of water in a particular location is generally facilitated by a discussion of regional precipitation. The δ values of $^2$H and $^{18}$O in water are generally obtained by collecting water samples from the source (wetland or lake) and determining isotopic signatures using IRMS or CRDS as mentioned above. The relationship between $\delta^2$H and $\delta^{18}$O for a particular water source is given by a linear equation ($\delta^2H=\delta^{18}O+d$). The *d* is the deuterium excess and is the independent term and corresponds to Meteoric Water Line. The value of *d* becomes higher when evaporation rates are high due to high temperature and low relative humidity. Therefore, *d* has a range of values for different climate, regions and season. For example, in the Mediterranean region summer rainfall water has higher *d* values (13.4‰) compared to spring rainfall (1.5‰) and reservoir water (9.77‰). If the rain comes from Atlantic it has a *d* around 10‰. In general, the *d* value of water depends on the source, mixing and pathways.

### APPLICATION OF Δ$^2$H AND Δ$^{18}$O TO STUDY WATER CYCLES IN WETLANDS

The source and dynamics of water in agricultural landscapes is one of the factors determine the placement of a wetland in the landscape. In this section, the role of water isotopic signatures to understand sources and dynamics of water in agricultural landscapes, and their roles in determining the ideal location of placing wetlands in the landscape. Isotopic signatures of $\delta^2$H and $\delta^{18}$O in water have long been used as naturally occurring tracers to assess the sources and fluxes of water in systems such as wetlands, rivers and lakes in agricultural landscapes, and to evaluate the origin of ground–water resources [43,44]. The variations in $^2$H and $^{18}$O contents in precipitation due to season and climate for a particular region generally results in what is called a 'local meteoric water line' (LMWL) relationship that can be linked to both surface and ground–water resources to assess the relative importance of precipitation contribution to water resources including wetlands [45].

In general, the evaporation of wetland water enriches the $^{2}H$ and $^{18}O$ (increases $\delta^{2}H$ and $\delta^{18}O$) contents in the remaining water leading to a systematic linear deviation from LMWL. This local evaporation line can be exploited to provide estimates of the relative magnitude of evaporation and water fluxes of wetlands in agricultural catchments. The following examples illustrate the application of $\delta^{2}H$ and $\delta^{18}O$ for establishing sources and fluxes of water in wetland systems. The information was obtained through the IAEA Coordinated Research Project (CRP) D1.20.10 on "Strategic placement and area–wide evaluation of water conservation zones in agricultural catchments for biomass production, water–quality and food Security".

The movement of water between a wetland and ground–water will affect the hydrology of wetlands. While different types of wetlands are developed to meet a set of objectives (water–quality, storage, irrigation) in agricultural catchment wetlands are mainly designed to capture and store water generated through runoff and probably used for irrigating water to crops around the pond. Therefore sufficient interaction between ground–water and wetland is important criteria as design consideration. Isotopic techniques play an important role to assess the exchange of water between the wetland and the ground–water as illustrated by the following example.

## REFERENCES TO ANNEX I


[I-1] MUCCIO, Z., JACKSON, G.P., Isotope ratio mass spectrometry. Analyst, **134** (2009) 213–222.

[I-2] WU, T., et al., Measurement of the D/H, $^{18}O/^{16}O$, and $^{17}O/^{16}O$ Isotope Ratios in Water by Laser Absorption Spectroscopy at 2.73 μm, Sensors, **14 (**2014) (5) 9027–9045.

[I-3] BOWEN, G.J., 2010. Isoscapes: spatial pattern in isotopic biogeochemistry, Annual Rev. Earth and Planetary Sci., **38** (2010) (1) 161–187.

[I-4] WASSENAAR, L. I., et al., Isotope hydrology of precipitation, surface and ground–waters in the Okanagan Valley, British Columbia, Canada. Journal of Hydrology, **411 (**2011) 37–48.

[I-5] CRAIG, H., Isotope variations in meteoric waters, Science **133 (**1961) 1702–1703.

[I-6] LIU, X.T., MA, X.H., Natural environmental changes and ecological protection in Sanjiang Plain (2002), Beijing, Science Press, (in Chinese).

## ANNEX II: MEDITERRANEAN WETLAND IN TUNISIA

The LMWL for precipitation in the Mediterranean region is provided in Fig. II-1. The straight line in the diagram obtained by linear regression (with an $R^2$=0.907) has a slope equal to 8 and is close to global meteoric water line (GMWL). However, the intercept (*d*–, 13.52) is above the GMWL (d–excess=10) suggesting that the *d* of precipitation is influenced by both Mediterranean (*d*–excess=22) and Atlantic (*d*=10) water masses. In the Mediterranean region, the major source of water for precipitation is the evaporation from the basin and the Atlantic Ocean. With slope of 8, the precipitation in this area is formed by mixing of both Mediterranean and Atlantic vapour masses.

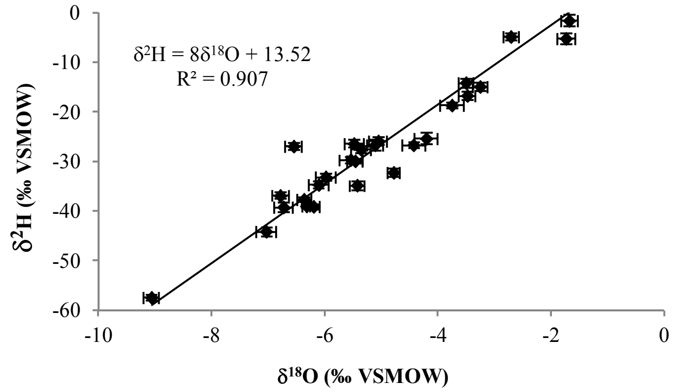



*FIG. II-1. Local meteoric water line for precipitation in the vicinity of a wetland in Mediterranean region (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

The plot of $\delta^2H$ vs $\delta^{18}O$ for water samples from runoff, overland flow and stream flow is shown in Fig. II-2. As shown in the figure most points lie very close to both LMWL and the GMWL (mostly between the two lines).

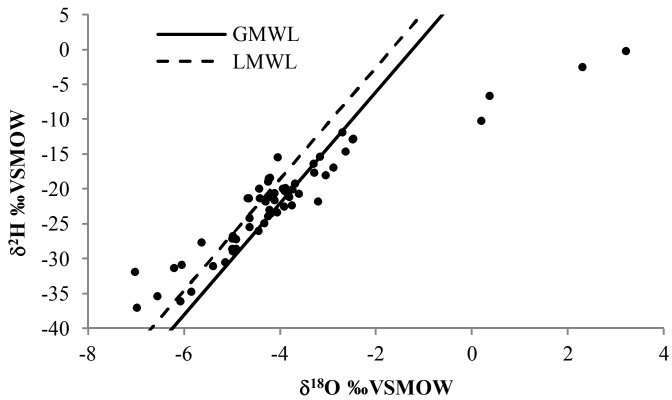



*FIG. II–2. Relationship between $\delta^2H$ and $\delta^{18}O$ for water samples collected during runoff events from September 2009 to June 2013 (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

This probably indicates that runoff, overland and stream flow originate from the precipitation. The plot of $\delta^2H$ vs $\delta^{18}O$ for water samples from the wetland is provided in Fig. II–3. There are 117 samples collected over a period of three years between 2009 and 2012. The slope of the waterline is inferior the slope of the GMWL and the LMWL indicating the local precipitation contributed to the lake water.

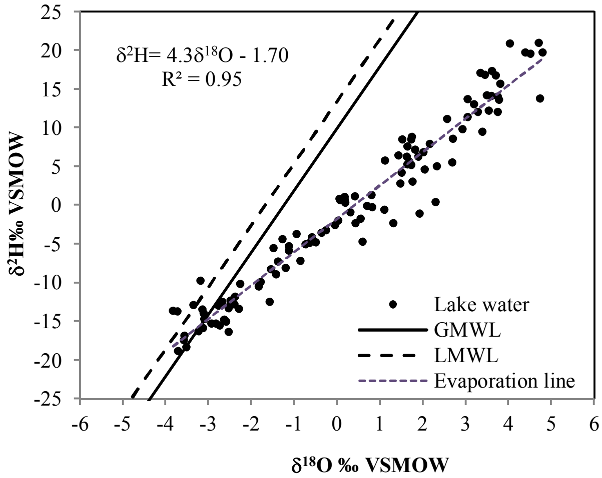



*FIG. II–3. Relationship between $\delta^2H$ and $\delta^{18}O$ for water samples collected from the wetland 2009 to 2012 (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

In summer, the water–level in the wetland drops due to its usage for irrigation and at the same time the water is enriched due to evaporation. Not all rainfall generated runoff at the catchment. However, all runoff generated are captured by the wetland. During the high–waters season (rainy periods), stable isotopes signal is fluctuating in relation with precipitation, stream flow, overland flow and probably releases volumes. However, during the low–waters season, the signal is continuously enriched (moving right) due to evaporation effect. During the high water season, the $\delta^2$H and $\delta^{18}$O of wetland water was almost close to both GMWL and the LMWN (Fig. II–*3*). Comparing both Figures II–*2* and II–*3* suggested that majority of water for wetland was derived from rainfall and runoff as shown by the slope and the *d*. So it is clear that rainfall to runoff to stream flow may be a major contributor to wetland water.

In this Mediterranean wetland catchment, ground–water was monitored in three locations namely (1) upslope, (2) around the wetland, and (3) downstream of the wetland. The $\delta^2$H and $\delta^{18}$O of ground–water at all three locations are provided in Fig. II–4

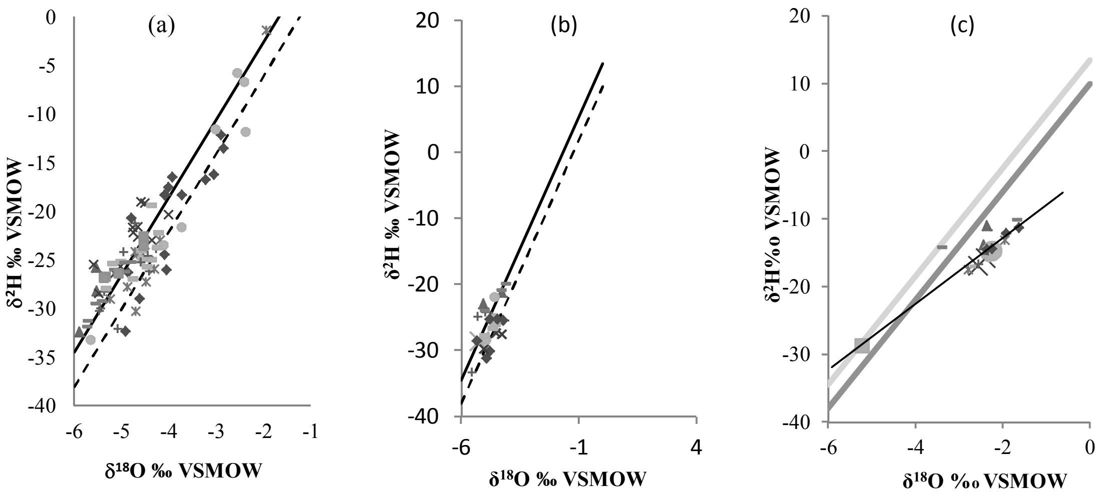



*FIG. II–4. Isotopic signatures of ground–water samples collected from upstream (a), around the wetland (b), and downstream (c) of the wetland (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

Ground–water samples collected from the upstream and around the wetland showed that $\delta^2H$ and $\delta^{18}O$ are stable and not influenced by hydrological processes (evaporation losses and recharge). In addition, there was no spatial variation of $\delta^2H$ and $\delta^{18}O$ observed in these areas (Fig *II-4a & b*). The $\delta^2H$ and $\delta^{18}O$ of water mostly fall between GMWL and the LMWL showing that the ground–water isotopic signatures are similar to the wetland water.

For the downstream part of the wetland, data plot below the local meteoric water line indicating an evaporation effect that could be explained either by the limited depth of the water table or by a direct recharge from the wetland (Fig. *II–4.*c). The isotopic signal of ground–water downstream of the wetland is close to that of lake but less enriched indicating that the recharge is likely a mixing between overflow, releases and infiltration. Stable isotope signal of ground–water located around the wetland used for the isotope budget are considered constant at a monthly scale. No seasonal variation is observed for these ground–waters. The isotopic signatures showed a recharge from wetland to ground–water in this region. While the $\delta^2H$ and $\delta^{18}O$ data showed that ground–water downstream of wetland was recharged (infiltration and overland flow and infiltration), it did not show that whether discharge from ground–water occurred to the wetland. Water balance estimation was carried out based on water input to and output from the wetland.

Using the equation (1) water balance was constructed to the wetland in the Mediterranean region and the water budget obtained for the period September 2009 to August 2010 is provided in Fig. *II–5*.

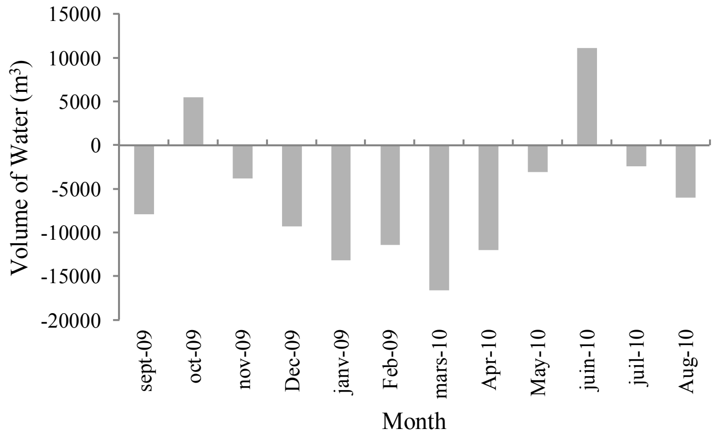



*Fig. II–5. Monthly water budget for the wetland system for the period September 2009 to August 2010 (courtesy of Laboratory of Radio Analysis and Environment, National School of Engineers, Sfax, Tunisia).*

The negative number in the graph showed that the wetland is recharging the ground–water and the positive number showed that the wetland is receiving ground–water. The graph showed that in October 2009 and June 2010, the wetland received water from the ground–water (discharge). It is to be noted that these two months are dry with very low or no rainfall. For the remaining period (mainly wet period), the wetland is recharging the ground–water.

It is clear from this water budget that areas which are favourable for the exchange of water between wetland and ground–water are an ideal location for wetland construction.

## ANNEX III: WETLAND WATER AND NUTRIENT BUDGETS AND IRRIGATION IMPROVEMENTS IN CASPIAN LOW LANDS

Assessment of sources and seasonal variations of wetland water and nutrient budget are fundamental for improving water quantity, quality and its agricultural use in the Southern Caspian lowlands of Islamic Republic of Iran. Ab–bandans (man–made wetlands) are used for water and nutrient harvest in the region. In this case study isotopic and conventional approaches have been used to identify sources of wetland water and to establish water and nutrient budget for thirty wetlands. The wetland water has been used to irrigate rice crops downstream. Water samples collected in autumn, winter, spring and summer from these wetlands were (i) analysed for N, P, $\delta^{18}O$ and $\delta^{2}H$, and (ii) constructed for water and nutrient balance.

The study used only 30 wetlands as more than thousand such wetlands exist in the area. These wetlands vary in size from 1 to 48 ha (Table III-1).

TABLE III-1. CHARACTERISTICS OF WETLANDS AND THE CATCHMENT IN ISLAMIC REPUBLIC OF IRAN

| **Characteristics** | **Range** | **Median** |
|---|---|---|
| Catchment area (ha) | 34–2547 | 239 |
| Annual precipitation (mm) | 1146– 431 | 1359 |
| Annual evapotranspiration (mm) | 763–831 | 792 |
| Wetland surface area (ha) | 1.1–48.12 | 4.83 |
| Volume of Water (million m3) | 0.009–0.743 | 0.375 |
| Depth of Water Column (m) | 0.43–6 | 0.8 |

Isotopic signatures of $\delta^{18}O$ and $\delta^{2}H$, and N and P for wetlands water measured for spring, summer, autumn and winter.

The $\delta^{18}O$ and $\delta^{2}H$ signatures of water in wetlands were lower in winter–autumn (dilution) than in summer–spring (evaporation) (Table III-2).

TABLE III-2. VARIATION IN ISOTOPIC SIGNATURES OF WATER IN PONDS DURING DIFFERENT SEASONS

| Season | Pond water isotopic signature | | |
|---|---|---|---|
| | $\delta^{18}O$ | $\delta^{2}H$ | d–excess |
| Spring | –3.57 | –27.72 | 0.83 |
| Summer | –1.15 | –12.11 | –2.9 |
| Autumn | –5.8 | –38.78 | 7.61 |
| Winter | –7.5 | –47.3 | 12.87 |

The average deuterium excess for pond waters (–7.54‰) was lower than that of the global meteoric water line (10‰) (Fig. III-1) indicating that rainfall/runoff was the main input to pond water and is further confirmed by isotopic signatures of rainfall, snow, ground–water and pond water during spring.

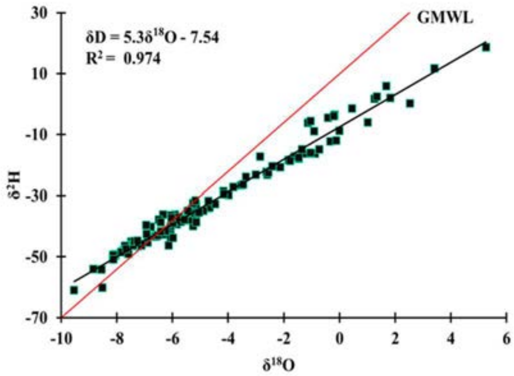



*FIG. III–1. Relationship between $\delta^{18}O$ and $\delta^{2}H$ for pond water in autumn, winter, spring and summer.*

All thirty wetlands together captured 7.6 million $m^3$ of water along with 86 tons of N and 17 tons of P annually which is used to irrigate up to 1650 ha of rice farms.

The case study showed that seasonal variation of $\delta^{18}O$ and $\delta^{2}H$ in wetland water probably depend on the input of rainfall in winter, snowmelt in spring, and summer pond evaporation. The relationship between $\delta^{18}O$ and $\delta^{2}H$, established for rain-water, snow and wetland water during spring season, suggested that wetland water is derived from rainfall/runoff and snow melt during spring.

## ANNEX IV: WATER–QUALITY ASSESSMENT UNDER RICE WETLANDS IN NORTH–EAST CHINA

The Sanjiang Plain in northeast of China is the largest food supply base in China. In the 1940s, more than 5 million ha of marshes and wet meadows existed in the plain [46]. However, in order to meet the food demand for the increasing population, part of the plain was reclaimed for agriculture. Since 1950s about 35% of wetlands in the plain have been converted for rice production. About 6.65 mega litres of ground–water $ha^{-1}$ has been extracted annually to meet the water demand for rice production in the region (corresponding to 665 mm) with an annual fertiliser application of 170 kg N $ha^{-1}$. Sustainable management of these rice wetlands is important to protect water resources. In this case study, isotopic signatures $\delta^{18}O$ and $\delta^2H$, water chemistry and depth of ground–water and surface water were monitored on three farms, namely, Honghe, Qianfeng and Qianshao (Fig. *IV–1)*.

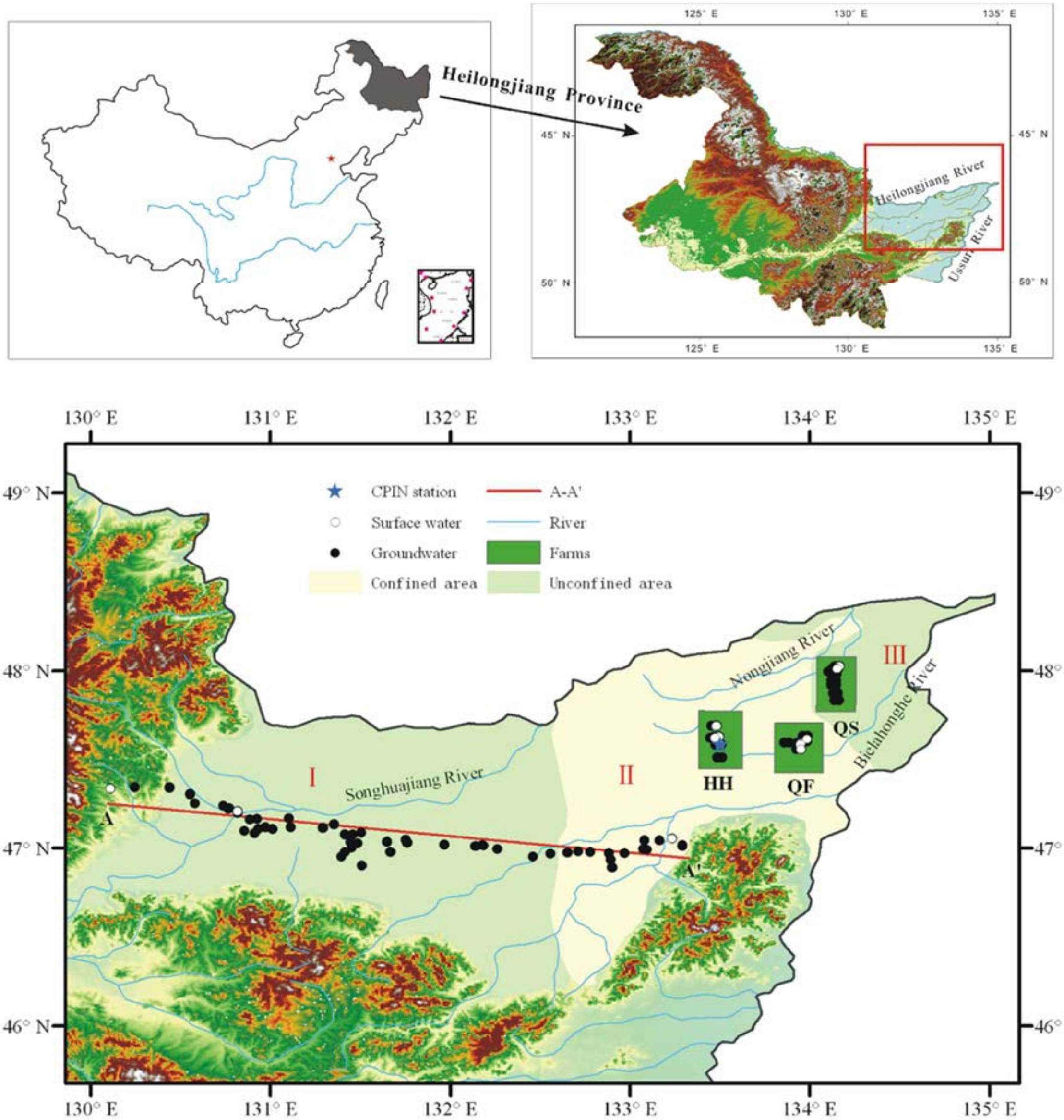



*FIG. IV–1. The Sanjiang Plain with the Nongjiang and Bielahonghe rivers and the three farms, namely Honghe, Qianfeng, and Qianshao.(courtesy of Liu, X.T. and Ma, X. H., Science Press, China)*

The total amount of dissolved anions and cations (total dissolved solids, TDS) in ground–water varied widely between the three farms compared with the differences in $\delta^{18}O$ and $\delta^2H$ in ground–water between these three farms. The channels and the paddy field also had similar $\delta^{18}O$ and $\delta^{2}H$ values as those presented in ground–water (Table 7).

TABLE IV-1. INITIAL ISOTOPIC SIGNATURES ($\Delta^{18}O$ AND $\Delta^{2}H$) AND TOTAL DISSOLVED SOLIDS FOR GROUND–WATER ON THREE FARMS

| Farm | Ground–water Depth (m) | $\delta^{18}O$ (‰) | $\delta^{2}H$ (‰) | TDS mg $l^{-1}$ |
|---|---|---|---|---|
| HH | 15 | –12.5 | –93 | 229 |
| QF | 18 | –12.8 | –97 | 231 |
| QS | 20 | –12.2 | –93 | 136 |
| HH–Paddy Field | | –11.1 | –80 | 103 |
| QF Paddy Field | | –10.6 | –79 | 89 |
| HH Channel | | –9 | –73 | 92 |
| QS Channel | | –9 | –77 | 93 |

Four categories of recharge to the ground–water are possible on Sanjiang Plain including local rainfall, river recharge, and irrigation returns from wetland rice and lateral ground–water flow (flow from the mountain areas with high altitude). According to the rainfall samples collected from Sanjiang station, modern rainfall can be characterized by the $\delta^{18}O$ and $\delta^{2}H$. The local meteoric water line (LMWL) is provided by the relationship $\delta^{2}H = 7.4\delta^{18}O–3$ (Fig. *IV–2*).

The annual weighted rainfall $\delta^{18}O$ and $\delta^{2}H$ values at Sanjiang station were –10.7‰ and –79.0‰, respectively. The $\delta^{18}O$ and $\delta^{2}H$ values of water for the Nongjiang River were –10.1‰ and –74.4‰, respectively and lay on the LMWL. The $\delta^{18}O$ values of irrigation water from rice wetlands entering the drainage channel ranged from of –9.0‰ to –12.6‰, with an average of –10.4‰. The $\delta^{18}O$ for all ground–waters collected from three farms ranged from –8.8‰ to –13.8‰ with an average of –12.4‰.

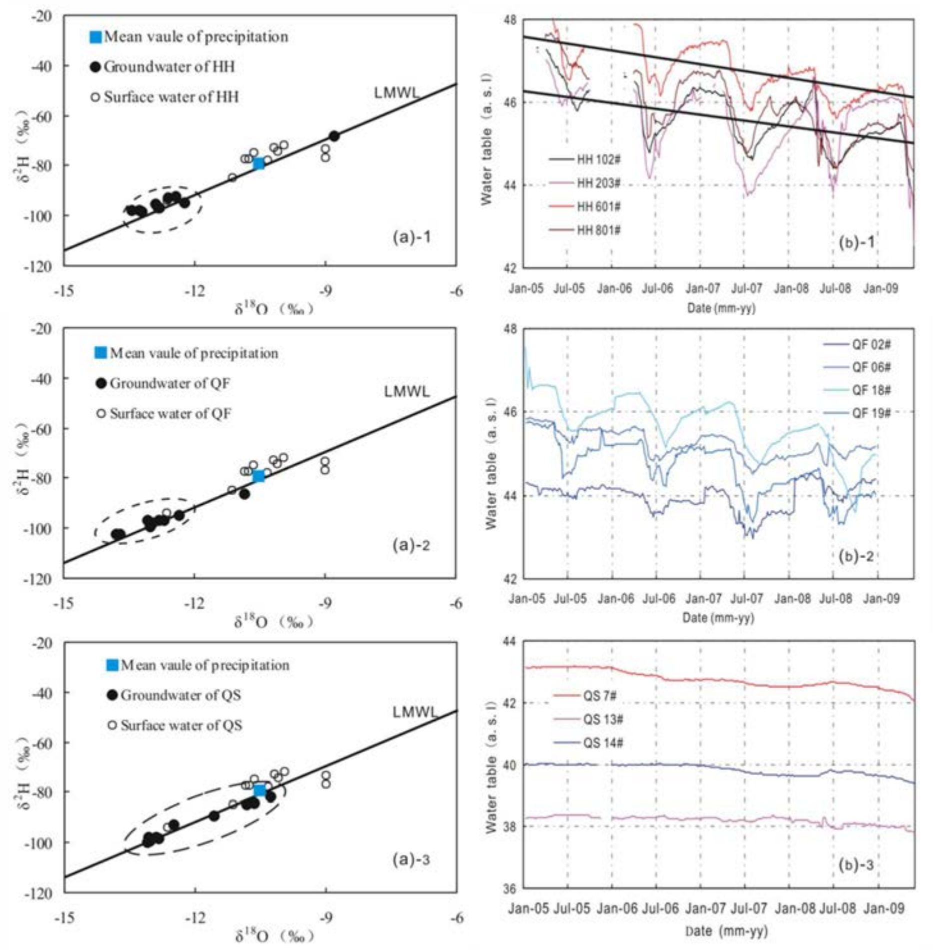



*FIG. IV–2 Isotopic signatures of precipitation and ground–water on Honghe, Qianfeng and Qianshao farms and ground–water depth regimes (LMWL) regression of $\delta^2H = 7.4\delta^{18}O–3.1$ with a correlation coefficient of 0.8 (n = 12).*

Stable isotope signatures of ground–waters collected from unconfined and confined areas displayed significant differences. In the confined area, $\delta^{18}$O values of ground–waters were depleted (average of –11.8‰) compared with the local weighted mean value for the rainfall (–10.7‰). On the other hand, in the unconfined area, the $\delta^{18}$O for ground–waters varied widely (–8.9‰ to –13.0‰), and a plot along a line with a slope of 5.3 had an intercept on the local meteoric water line at –11.8‰ (*FIG. IV–3*), which is identical to the mean value of ground–waters sampled in the confined area. These data suggest that the Sanjiang Plain aquifer is significantly recharged by the high altitude precipitation from the surrounding mountain which is characterized by depleted isotopic signatures. However, in the unconfined area, extra recharge exists and the ground–water system is recharged from the land surface by rainfall or by infiltration from rivers, irrigation or a combination of each.

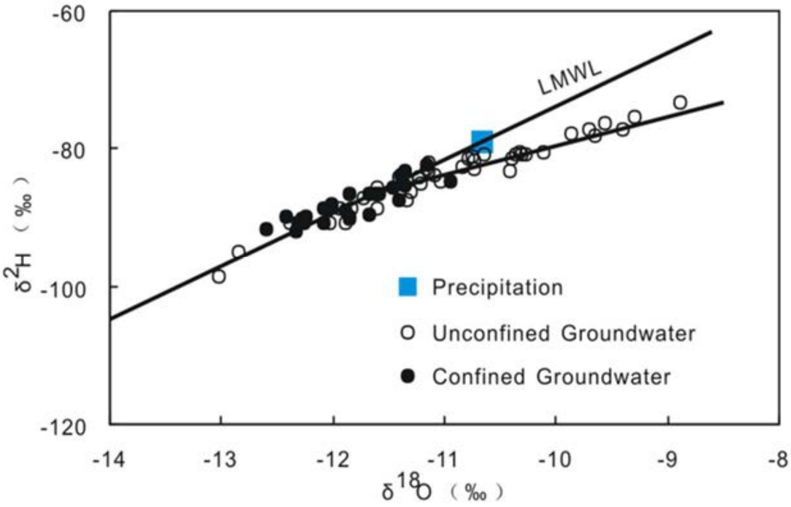



*FIG. IV–3. Plot of $\delta^{18}O$ and $\delta^{2}H$ of ground–waters from the Sanjiang Plain.*

Limited vertical infiltration (leaching) of water from rice wetlands reduced the influence of agricultural activities on the $NO_3^-$contamination of ground–waters. The low levels of $NH_4^+$ in surface waters (wetlands and channels) and of $NO_3^-$ in ground–waters near the river are probably attributable to $NO_3^-$ and $NH_4^+$ retention in wetland. With certain wetland coverage, ground–water quality is safe for wetland drainage and agricultural transformations on the Sanjiang Plain.

## CONTRIBUTORS TO DRAFTING AND REVIEW

| | |
|---|---|
| Chkir Ben Jemaa, N. | University of Sfax, Tunisia |
| Fasina, A. | University of Ado Ekiti, Nigeria |
| Gheorghe, I.F. | Ecological University of Bucharest, Romania |
| Gold, A.J. | University of Rhode Island, United States of America |
| Grünberger, O. | Montpellier Supagro, France |
| Mander, U. | University of Tartu (Ut), Estonia |
| Mousavi Shalmani, M.A. | Atomic Energy Organization of Islamic Republic of Iran (AEOI), Islamic Republic of Iran |
| Pang, Zh. | Chinese Academy of Sciences, China |
| Pinay, G. | Observatoire des Science de l'Univers De Rennes, Osur – Ecobio, France |
| Reddy, K. R. | University of Florida, United States of America |
| Tenywa, M. | Makerere University, Uganda |

# ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

**BELGIUM**
***Jean de Lannoy***
Avenue du Roi 202, 1190 Brussels, BELGIUM
Telephone: +32 2 5384 308 • Fax: +32 2 5380 841
Email: jean.de.lannoy@euronet.be • Web site: http://www.jean-de-lannoy.be

**CANADA**
***Renouf Publishing Co. Ltd.***
22-1010 Polytek Street, Ottawa, ON K1J 9J1, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: http://www.renoufbooks.com

***Bernan Associates***
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

**CZECH REPUBLIC**
***Suweco CZ, s.r.o.***
SESTUPNÁ 153/11, 162 00 Prague 6, CZECH REPUBLIC
Telephone: +420 242 459 205 • Fax: +420 284 821 646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

**FRANCE**
***Form-Edit***
5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: fabien.boucard@formedit.fr • Web site: http://www.formedit.fr

***Lavoisier SAS***
14 rue de Provigny, 94236 Cachan CEDEX, FRANCE
Telephone: +33 1 47 40 67 00 • Fax: +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

***L'Appel du livre***
99 rue de Charonne, 75011 Paris, FRANCE
Telephone: +33 1 43 07 43 43 • Fax: +33 1 43 07 50 80
Email: livres@appeldulivre.fr • Web site: http://www.appeldulivre.fr

**GERMANY**
***Goethe Buchhandlung Teubig GmbH***
Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 874 015 • Fax: +49 (0) 211 49 874 28
Email: kundenbetreuung.goethe@schweitzer-online.de • Web site: http://www.goethebuch.de

**HUNGARY**
***Librotrade Ltd., Book Import***
Pesti ut 237. 1173 Budapest, HUNGARY
Telephone: +36 1 254-0-269 • Fax: +36 1 254-0-274
Email: books@librotrade.hu • Web site: http://www.librotrade.hu

**INDIA**
***Allied Publishers***
1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 4212 6930/31/69 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

***Bookwell***
3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: http://www.bookwellindia.com

**ITALY**

***Libreria Scientifica "AEIOU"***
Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: http://www.libreriaaeiou.eu

**JAPAN**

***Maruzen-Yushodo Co., Ltd.***
10-10, Yotsuyasakamachi, Shinjuku-ku, Tokyo 160-0002, JAPAN
Telephone: +81 3 4335 9312 • Fax: +81 3 4335 9364
Email: bookimport@maruzen.co.jp • Web site: http://maruzen.co.jp

**RUSSIAN FEDERATION**

***Scientific and Engineering Centre for Nuclear and Radiation Safety***
107140, Moscow, Malaya Krasnoselskaya st. 2/8, bld. 5, RUSSIAN FEDERATION
Telephone: +7 499 264 00 03 • Fax: +7 499 264 28 59
Email: secnrs@secnrs.ru • Web site: http://www.secnrs.ru

**UNITED STATES OF AMERICA**

***Bernan Associates***
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

***Renouf Publishing Co. Ltd.***
812 Proctor Avenue, Ogdensburg, NY 13669-2205, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: http://www.renoufbooks.com

**Orders for both priced and unpriced publications may be addressed directly to:**

IAEA Publishing Section, Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

17-04391

International Atomic Energy Agency
Vienna
ISBN 978-92-0-100917-3
ISSN 1011–4289