1 GENERAL INTRODUCTION

1.1 Wetland ecosystems

Wetlands comprise 6% of the Earth's surface (Williams, 1990). They are transitional between terrestrial and aquatic systems, and predominantly support hydrophytes, at least periodically. They occur in areas where soils are naturally or artificially inundated or saturated by water due to high groundwater or surface water during a part of or throughout the year. Wetlands are common in river deltas and estuaries, floodplains, tidal areas, and are widespread in riverbeds, depressions, foot slopes, and terraces of undulating landscapes. Wetland ecosystems may be discriminated on the basis of hydrology, soils, and vegetation and include swamps, marshes, bogs, fens, floodplains, and shallow lakes (Mitsch and Gosselink, 1993; Neue et al., 1997).

The Ramsar Convention defines wetland as marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceeds six meters (UNESCO, 1994). In agricultural ecosystems, wetlands may be defined as having free water at or near the surface for at least the majority of the growing season of arable crops, or for at least 2 months of the growing season of perennial crops, grassland, forest, or other vegetation. The water is shallow enough to allow growth of a crop or natural vegetation rooted in the soil. Free water may occur naturally or may be retained by: field bunds, puddled plow layers, traffic pans from rainfall run-off, or irrigation sources (Neue et al., 1997).

Tropical wetlands have at least one wet growing season per year but may be dry, moist or without water in other seasons. Wetland soils may therefore alternately support wetland and dryland plant species. Therefore, wetlands are ecotones. The boundary between wetland and dryland is often gradual, and may fluctuate from year to year depending on variations in precipitation. If water (drainage and irrigation) can be fully controlled it is within the farmer's discretion to establish either wet- or drylands. Despite that, the drainage capacities of most tropical wetlands are insufficient to prevent periodic soil submergence during the rainy season (Neue et al., 1997). This is due to lack of resources and understanding of the functioning of the wetland ecosystem.

Wetland aerial estimate is uncertain given the broad definition of wetlands (Mitra et al., 2003). Each country should formulate its definition based on the international definition. The Ramsar Convention requires all its parties to adopt and adapt the definition as is relevant to their territory. Each party is also required to make an inventory of wetlands within its territory and ensure the wise use of such wetlands. The contracting parties shall encourage research and the exchange of data and publications regarding wetlands and their flora and fauna. They shall also promote the training of personnel competent in the fields of wetland research, management and wardening (UNESCO, 1994).

1.1.1 Wetland types of Africa

The largest wetlands of Africa are the Sudd Swamp of Sudan, the Okavango Delta of Botswana, the Kafue/Bangweulu floodplains of Zambia, and the swamp forests of Zaire (Figure 1.1). East Africa contains wetlands that are smaller in size but nevertheless important in their ecological structure and functioning such as lowland valley swamps on the fringes of Lake Victoria (mostly in Uganda but a few on the eastern shores of Kenya) (Haper and Mavuti, 1996). Although wetlands of many types are found in Tropical Africa, the most distinct is perhaps the papyrus marsh (Williams, 1990). Papyrus (*Cyperus papyrus*) is a large sedge 3-5m in height but sometimes 10m (Jones and Humphries, 2002). It grows in dense stands along lake edges, most commonly in the vicinity of Lake Victoria. Papyrus marshes are absent in West Africa and the great riverine swamps of the Congo Basin.

Papyrus has a C4 photosynthetic pathway, an efficient mechanism found in most tropical grasses for fixing derivatives of atmospheric carbon-dioxide. Concentrations of nitrogen, phosphorus and other minerals are low in papyrus and other emergent macrophytes (Williams, 1990). However, papyrus concentrations of these elements are low within the macrophyte group, suggesting great efficiency in achieving growth under low nutrient conditions.

Papyrus also shares with other macrophytes the ability to extract minerals from infertile waters and sediments and to release, through decay and exudation, organic compounds that serve as energy sources for a variety of diverse consumer food chains, which in many places include humans.

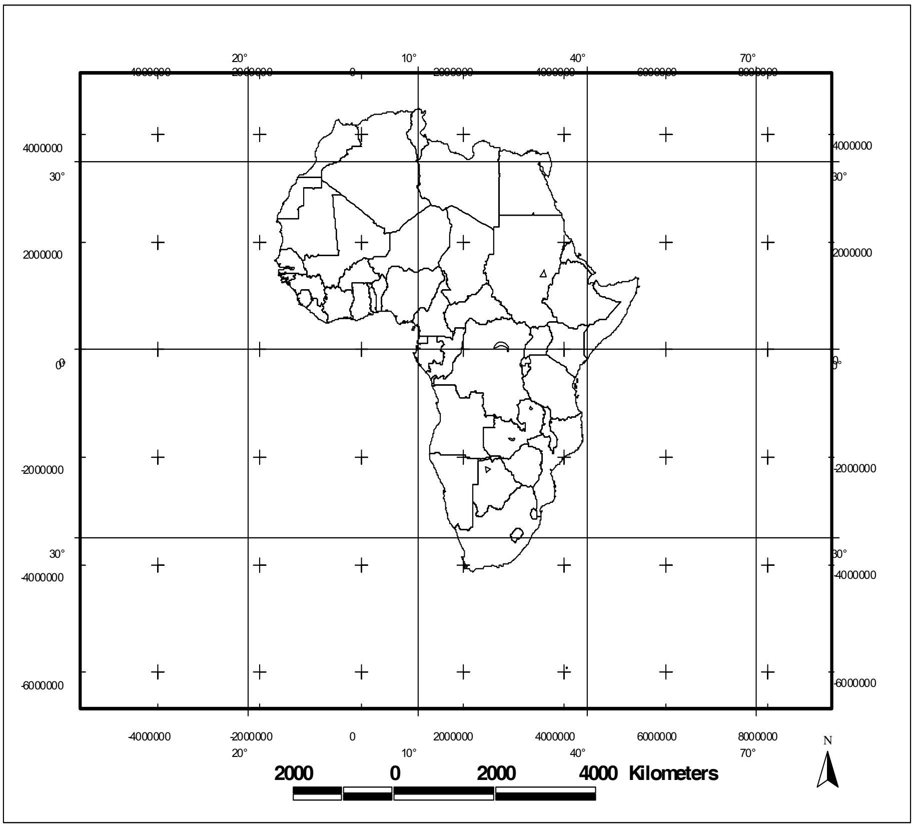

Figure 1.1: The largest wetlands of Africa (modified from Harper and Mavuti, 1996)

One of the major functions of wetlands is the enhancement of water quality by the trapping of suspended sediments in runoff from adjacent upland systems (Perison et al., 1997). Along Lake Victoria, well-developed papyrus marshes effectively remove sediments from water flowing in from adjacent savannahs, releasing high quality waters to the lake. Light intensity near the ground of the marsh is low. Therefore, efficiency of light capture by papyrus is high. Peat frequently develops beneath papyrus, sometimes accumulating to over 1m in depth. Peat accumulation is less obvious along lake edges and in open waters where papyrus forms a floating mat. In valley bottoms, papyrus peat is attractive for agriculture.

1.1.2 Wetland soils

The protection of wetland soils requires greater attention if soil C storage is to be increased in the humid tropics (van Noordwijk et al., 1997). Wetland soils are hydric soils, i.e. soils formed under conditions of saturation, flooding or ponding, long enough during the growing season to develop anaerobic conditions in the upper part (USDA, 1993). Hydric soils can be either organic or mineral soils. Organic soils formed in waterlogged situations, where decomposition is inhibited and plant debris slowly accumulates are called Histosols. All Histosols are hydric soils except Folists, which are freely drained soils occurring on dry slopes where excess litter accumulates over bedrock. Mineral hydric soils are those soils periodically saturated for sufficient duration to produce chemical and physical properties associated with a reducing or anaerobic environment.

Wetlands are complex ecosystems exhibiting considerable spatial variability. The soils there are physically unstable and in constant flux (Williams, 1990). A number of factors control the spatial relationships in these systems, making the separation of systematic from random soil components difficult. Systematic spatial relationships in wetland soils are the result of differences in parent material, elevation, erosional or depositional environment, frequency of flooding, vegetation, pedogenic effects, and hydrology (Stolt et al., 2001). Random effects are attributed to unrecognized differences in these parameters, as well as differences due to sampling and laboratory error. These random effects often obscure or confound soil-elevation, soil-vegetation, or soil-hydrology relationships. Therefore, to understand spatial relationships in wetland soils, random variability needs to be recognized and separated from systematic variability. A considerable difference in soil parameters can exist within a wetland area, even if the change in elevation is minimal (Stolt et al., 2001). For instance, significant differences in organic carbon and clay content occur between depressional wetland and a surrounding upland rim.

Wetland soil properties

Soil properties are strongly related to retention and movement of water within the soil system. Water serves as one of the primary energy sources for landscape processes, such as sequestration of organic carbon, erosion, colonization of vegetation, and distribution of soluble and mobile compounds (Reuter and Bell, 2001). The interaction between water level, sedimentation and decomposition is finely balanced, and within the soil there are biochemical processes at work such as energy flows through the ecosystem leading to the transformation and trapping of nutrients (William, 1990). The soil attributes that control nutrient availability in soils are organic matter content, soil moisture, pH, texture, sesquioxides content, and the type and amount of clay minerals (Iggy Litaor et al., 2002). Wetland soil development and properties are influenced by temporary or permanent saturation within the upper part of the pedon. If anaerobic conditions impose permanent characteristics on the soil, the term gley-phenomena or hydromorphic properties are commonly used (Neue et al., 1997). Gleyed soils develop when anaerobic soil conditions result in the pronounced chemical reduction of iron, manganese and other elements, thereby producing gray soil colors (USDA, 1993). Sulfidic material is present when mineral soils emit an odor of rotten eggs (hydrogen sulfide). Such odors are only detected in waterlogged soils that are permanently saturated and have sulfidic material within a few centimeters of the soil surface.

The correlation between water status, landscape and soil properties is well documented in pedologic studies (Reuter and Bell, 2001). Such studies indicate that correlation persists across land types and geographic locations. Landscape position and terrain attributes affect the distribution of soil properties such as A-horizon thickness and clay and organic carbon content. Also, a correlation exists between depth to water and soil color patterns in drainage basins. The relationships between duration and season of occurrence of soil saturation with soil color patterns are documented (Reuter and Bell, 2001). Trend surface analysis indicates significant relationships among elevation, vegetation, and soil chemical properties across a wetland (Stolt et al., 2001). A study by Brunet and Astin (1997) indicated that the vegetation strip on the flood zone of the Adour River accumulated large quantities of sediments with total nitrogen and carbon contents of 4mg/g and 30mg/g, respectively. The concentrations were found to vary as a function of topography and vegetation. The floodplains received less sediment but the observed concentrations of nitrogen and carbon were more variable and found in the range of 1-9 mg/g and 10-82 mg/g, respectively. The highest levels were found in wooded areas of the floodplain. A study by Davidson (1995) found that drainage class or soil wetness distinguished between C-rich and C-poor soils.

Spatial variability is important to consider when assessing the environmental and ecological functions of a wetland. Many wetland functions, such as floodwater storage, traps of sediments, and sinks of various non-point pollutants are difficult to measure directly. In lieu of direct measurements, soil and landscape properties can be recorded and then related to the potential of the wetland to function in one or more of these capacities (Stolt et al., 2001). The nature of the spatial variability must be considered to ensure that the full range of soil, landscape, and associated wetness conditions are described. Natural wetlands that are known to serve a number of functions are now used to serve as reference wetlands. Reference wetlands provide natural comparative sites for use as a marker of success or failure of adjacent wetlands.

Classification of wetland soils

Soil classifications do not deal with wetland soils but with hydromorphic soils, i.e. soils with defined long-lasting signs of periodically or permanently reducing soil conditions. Reducing conditions may not occur in soils or within wetland soils that contain considerable dissolved oxygen, lack decomposable organic matter in combination with high contents of calcium carbonates, or other factors that suppress the reducing activity of microorganisms (Neue et al., 1997). Many rice-growing countries have developed classification systems that discriminate between naturally wet and rice (paddy) soils (Sanchez and Buol, 1985). The only soil systems applicable worldwide are the Legend of the FAO-UNESCO Soil Map of the World (FAO, 1974) and the Soil Taxonomy (USDA, 1975).

In the FAO-UNESCO Legend for the Soil Map of the World (FAO, 1974), the Gleysols, Fluvisols, Planosols, and Histosols make up most of the wetland soils. Gleyic subunits of Acrisols, Luvisols, or Podzols are mostly wetland soils, too. Following the FAO nomenclature, a typical soil profile of a mineral wetland soil after weeks of flooding is as follows (Neue et al., 1997):

Horizon	Description
Afw	A layer of standing water (letter suffix ‘fw’ for floodwater) that becomes the habitat of bacteria, phytoplankton, macrophytes (submerged and floating weeds), zooplankton, and aquatic invertebrates and vertebrates. The chemical status of the floodwater depends on the source, soil, nature and biomass of aquatic fauna and flora, and cultural practices. The pH of the standing water is determined by the alkalinity of the rain or irrigation water,

soil pH, algal activity, and fertilization. As a result of algal growth and aquatic weeds, the pH and oxygen content undergo marked diurnal fluctuations. In the daytime, pH may reach above 10, and the standing water becomes over saturated with oxygen due to photosynthesis of the aquatic biomass. Standing water stabilizes the soil water regime, moderates the soil temperature regime and prevents soil erosion.

Aox A thin floodwater aerated soil interface (letter suffix 'ox' for oxidized) that receives sufficient oxygen from the floodwater to maintain pE + pH above the range where NH_4^+ becomes the most stable form of N. The thickness of the layer may range from several mm to several cm depending on pedoturbation by soil fauna and the percolation rate of water. Major processes are aerobic decomposition of organic matter, photodependent biological N_2^- fixation by algae and photosynthetic bacteria, nitrification by ammonium and nitrate oxidizers, and methane oxidation.

Ag A reduced layer (letter suffix 'g' for gleyic) that is characterized by the absence of free O_2 in the soil solution. The Eh of the soil solution is less than 300 mV, reduction processes predominate and the pE + pH is low enough to reduce iron oxides.

Ax This layer (letter suffix 'x' for deoxygenated) has increased bulk density, high mechanical strength, and low permeability. In cultivated soils it is frequently referred to as the plow pan or traffic pan. NH_4^+, Mn^{2+}, Fe^{2+} and, if the Eh is low enough, even sulfides and CH_4 are stable chemical forms.

B The characteristic of the B-horizon is highly dependent on the water regime. In epiaquic moisture regimes, the horizon generally remains oxidized, and redoximorphic features occur along cracks and in wide pores. In aquic moisture regimes, the whole horizon or at least the interior of soil peds remains reduced during most years.

Histosols (organic soils) are much less well defined. About 10% of the world's histosols are being farmed while only 5% of organic soils in the tropics may be used for rice farming and grazing. Clay minerals underlie most shallow histosols. These have