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New Approaches to Agricultural Land Drainage: A Review

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Abstract

A review on agricultural effects of restricted soil drainage conditions is presented, related to soil physical, chemical and biological properties, soil water availability to crops and its effects on crop development and yield, soil salinization hazards, and the differences on drainage design main objectives in soils under tropical and semi-arid water regime conditions. The extent and relative importance of restricted drainage conditions in Agriculture, due to poor irrigation management is discussed, and comprehensive studies for efficient drainage design and operation required are outlined, as related to data gathering, revision and analysis about geology, soil science, topography, wells, underground water dynamics under field conditions, the amount, intensity and frequency of precipitations, superficial flow over the area to be drained, climatic characteristics, irrigation management and the phenology of crop productive development stages. These studies enable determining areas affected by drainage restrictions, as well as defining the optimal drainage net design and performance, in order to sustain soil conditions suitable to crops development.

Keywords: Restricted drainage; Drainage studies; Drainage design parameters

Introduction

Agricultural land drainage consists of a set of technical strategies and hydraulic structures allowing the removal of water and/or salts excesses present in the soil volume occupied by crop roots, to provide an adequately oxygenated environment suitable for root normal development, keeping adequate water and air relative proportions according to crop physiological needs, to enable soil sustainability for crop productive conditions [1-4]. Under deficient drainage conditions, resulting from excessive water stored in the soil pore space, oxygen vapor pressure is very limited for root crop normal biological activity, as well as for the microflora and microfauna activity in soil [5]. This condition induces multiple physiological disorders in plants, such as stomata closure induction processes in leaves, due to the increase in the ABA (abscisic acid) concentration, as well as to a lower permeability of root exodermis cell membranes to water and nutrient absorption [6-8].

Anoxia conditions in soils inhibit root tissue respiration rates and energetic processes at the cellular level [9], thus affecting important metabolic processes in plants, which react to the oxidative stress using an unique substrate for the ADP phosphorylation to ATP, and thus generating metabolic energy disorders, resulting in fermentative glycolysis instead of oxidative respiration [10,11]. As a consequence, plant photosynthetic rate is inhibited [11,12] and the transport of solutes among plant organs, through its conductive phloematic and xylematic tissues, is significantly reduced, modifying transport and storage mechanisms of photosynthates and minerals in the whole plant [13,14]. It has been also demonstrated that oxygen deficiencies induce photo-oxidative damage in leaves, due to the generation of reactive oxygen species (ROS) such as superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH^-), which affect chloroplast fundamental functions, resulting in significant levels of chlorosis and premature senescence induction in plant tissues [15]. Another important effect of oxygen deficiency is the generation of plant chemical signals, stimulating ABA production in leaves, which activate stomata closure mechanisms, further decreasing photosynthetic rates and transpiration [16]. For soils under limited aeration conditions, an increase in CO_2 concentration is produced inside the soil porous volume, with a transient increment of pH around the root absorbing system [10,12]. Also, accumulation of others gases in the soil has been reported, such as methane and hydrogen sulfide, generated during anaerobic degradation of soil organic matter, which may have phytotoxic properties, causing environmental damage in flooded soils [17].

As a result of plant metabolic disorders, caused by conditions of total or partial anoxia near the roots, resulting from deficient drainage conditions, a decrease in crop production often occurs [8,15,16,18]. In anoxic or hypoxic soils, one of the earliest detectable changes is the decline in net CO_2 assimilation rate, as reported for diverse crops such as avocado (Persea americana Mill) [8], sunflower (Helianthum annus L) [19] beans (Vigna radiate) [9]. This reduction is often coupled to decreases in stomata conductance, transpiration rate and intercellular CO_2 partial pressure in leaves) [20]. In poorly drained soils, the intrinsic dependence between water content, apparent density and porosity also affect soil physical and hydrodynamic properties, such as major changes in soil structure, reducing its permeability and temperature fluctuations, with significant impacts on crop development and yield [5,6,21,22]; under low soil temperature, chemical and biological reactions rates decrease drastically [23,24]. Severe restrictions on the uptake of major plant nutrients, like nitrogen, phosphor, sulfur and calcium, have been reported in cold, poorly drained soils [25]. Microorganisms responsible of soil organic matter degradation are influenced by changes in the soil environment; low temperature and anaerobic conditions restrict microorganism activity and abundance. A decrease in soil temperature, resulting from waterlogging, produces a proportional decrease in organic matter decomposition rates [26,27].

In poorly aerated soils, high concentrations of mineral elements in reduced forms (Fe^{+2}, Al^{+3}, and NH_4^+) are common [17]. Oxygen diffusion into saturated soil is extremely low, therefore, as depth in the saturated soil profile increases, the presence of O_2 diminishes and the redox potential turns extremely low. Moreover, the soil may lose some of its soluble nitrogen species, due to an oxidation of ammonia nitrogen to both nitric and nitrous species, followed afterwards by a reduction of these N-species to various forms of gaseous nitrogen, producing a release of gaseous nitrogen to the atmosphere [25]. Reduction-

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reactions predominate over oxidation-reactions in soils presenting drainage restrictions, so when iron is present in its Fe^{+2} form (reduced), a gray-bluish tint can be observed in the soil; the opposite occurs when oxidation reactions prevail, with changes in soil color, from reddish to brown tints. When alternate periods of poor and adequate drainage develop throughout the year, the soil profile exhibits some very characteristic stains of yellowish–orange appearance; for permanent saturation conditions the dominant soil color is gray and these soils are generically known as *gley* soils [28,29].

Waterlogging in soils is the major factor influencing soil compaction process [30,31], which is defined as the process in which soil particles organize themselves spatially, diminishing void spaces in soils, thus increasing its apparent density; in other words, the increase in soil moisture content reduces its capacity to support loading and decreases the permissible pressure due to mechanical work [31]. High levels of soil compaction are related to soil penetration resistance [32]. Soil compaction is mainly produced by tillage activities and machinery weight, that is transmitted to soil either through the wheels or others contact elements; agricultural machinery traffic intensity is determinant for soil compaction problems in poorly drained soils [33]. Soil tillage is often needed to maintain optimal aeration within the soil rooting profile [30,31,34]; in clay soils, intensive plough use at a specific depth generate a compacted, almost impermeable soil layer located immediately below plough depth, which restricts both crop root development, as well as the free water and air flow within the profile [35,36]. Soil profiles accumulate dissolved salts present in phreatic layers; in arid and semiarid regions, these salts may ascend by capillarity from the phreatic layers into the soil volume occupied by crop roots; the existence of a saline phreatic mantle is frequent at soil depressions [37]. Gradual soil salinization resulting from deficient drainage conditions can occur [3,38-41]; main salts present in poorly drained soil profiles correspond to sulphates [42], nitrates [43], chlorides [44], carbonates and bicarbonates [45]. Gradual soil salinization, and the eventual crystallization of salts [40,46], when its concentrations exceed the pK values for specific saline solutions, is produced as the result of water absorption by crops, which normally excludes most of the salts, by means of its selective root permeability [47,48], as well as by salt free water direct evaporation from the soil surface [1,49]. Soil salinization processes also modify soil structure, leading to a gradual impairment in its agricultural productivity, because high salt concentrations can disperse clay soil aggregates, reduce soil porosity and permeability [38,39], reduce water availability to crops and can be phytotoxic. These phenomena originate crusting and hardening of the soil surface, incrementing soil resistance to penetration and reducing soil gaseous exchange with the atmosphere, as well as reducing soil water infiltration rate [50]. Saline and sodic soils not only are physical and chemically degraded, but also can be biologically affected, due to reduced concentration and activity of heterotrophic microorganisms. Organic matter decomposition rate in poorly drained soils is considerably lower, as compared to soils with normal aeration conditions [51]. A decrease in soil fertility and nutrient supply to crops occurs with deficient drainage conditions, and larger rates of crop fertilizer needs are needed to reach profitable crop yield [52,53].

Removal of waterlogging conditions in soils though agricultural drainage, is crucial for efficient and sustainable crop production in irrigated areas, both in tropical zones as well as in rain-fed zones, were crops satisfy its hydric requirements exclusively from precipitations [39,54,55]. In some areas, soil drainage is produced naturally, but in other areas, soil intervention is necessary to create conditions for an efficient artificial drainage [3,56]. In tropical regions, precipitation generally is larger than evapotranspiration; for low hydraulic conductivity soils, superficial drainage problems are common. In these areas, the excess of precipitations nearly always guarantees that saline balance in soil is kept, so drainage main purpose in these areas is to evacuate water from the soil profile and to provide the ideal aeration conditions in the soil profile [57]. On arid and semi-arid zones, atmospheric evaporative demand is high and precipitations are scarce; generally the yearly total precipitation is significantly lower than crop evapotranspiration. Agricultural activity is only possible by implementing irrigation, to acknowledge for hydraulic balanced conditions, enabling crops reach profitable yields. Excessive irrigation determines saturation conditions to develop, thus raising phreatic levels in the soil profile [1,46]. Moreover, in arid and semiarid areas, irrigation water with significant salt concentrations can generate soil productivity degradation and crop reduced water availability, by a decrease of soil water potentials [7,46,58]. Therefore, artificial drainage in this areas is aimed towards reducing phreatic levels and eliminate salinity from the soil profile occupied by crop rooting systems [38,39,59].

Artificial agricultural drainage design in tropical and arid zones share common principles, but there are important differences in drainage system design and planning objectives. The main goal on tropical zones is soil profile waterlogging control, to provide ideal aeration conditions for crops; in arid zones and semi - arid zones, drainage not only includes soil aeration considerations, but also it must consider salinity control and soil moisture deficit avoidance [60].

Agricultural drainage plays an important role on world food production, providing a safeguard for investments in irrigation, as well as the conservation of soil resources. During the XX century second half, large drainage projects were built worldwide, on about 150 million hectares affected by flooding and salinity problems, thus contributing to world food production significant improvements, by intensifying and diversifying competitive and financially sustainable agricultural activities. Soil profile artificial intervention, associated to the annexed hydraulic structures needed to eliminate the drained water, represent significant public and private investments, oriented to solve deficient agricultural drainage situations [2,54,57]. Therefore, it is essential that drainage systems should be properly designed, installed, operated and maintained. Planning and design of drainage networks determines the efficiency of water and salinity removal from agricultural soil profiles [4,53,54,57]. In developing countries, most drainage facilities are far from being adequate or sufficient; only 14% of the 1.500 million hectares cultivated worldwide, including both irrigated and non-irrigated lands, have been implemented with some kind of drainage structures (Figure 1) [60]. Agricultural soils subsurface drainage systems must include quantitative information on relevant aspects of hydraulic engineering,

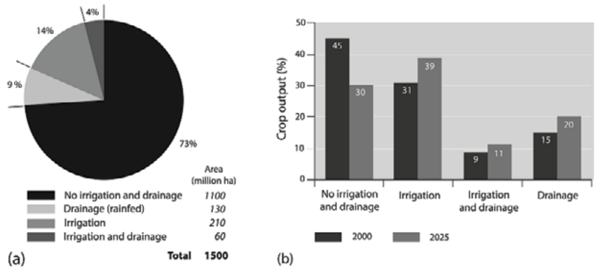

Figure 1: Drainage plays an essential part to sustainable food production: (a) Worldwide total agricultural areas. (b) Relative agricultural output from agricultural lands provided with irrigation and drainage systems in 2000 and in 2025 [60].

1. Topographic Studies	i. Slope constraints
	ii. Landscape
2. Investigation of soils	i. Soil maps
	ii. Soil salinity and alkalinity data
	iii. Oxidation - reduction potential data
	iv. Soil composition
	v. Hydraulic conductivity measurements
3. Origin of the water present in soil profile	i. Precipitations
	ii. Deficient irrigation
	iii. Underground water (aquifer)
4. Studies of underground waters	i. Water table relative location in the soil profile
	ii. Water table level and flow fluctuations
	iii. Water table salinity fluctuations
5. Irrigation practices and requirements	i. Irrigation water quality
	ii. Irrigation type and frequency
	iii. Irrigation water depths applied
	iv. Water depth requirements for salinity control
	v. Water losses due to percolation
	vi. Irrigation techniques

Table 1: Main studies relative to the design and planning of drainage systems [53].

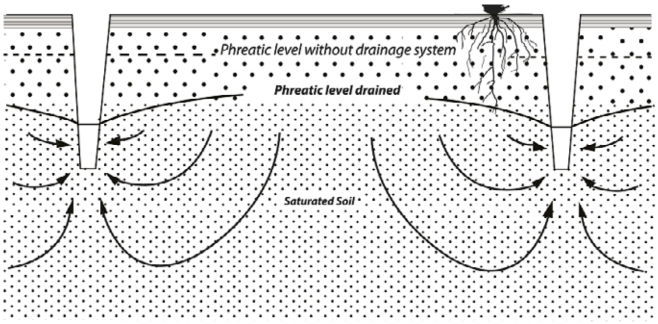

Figure 2: Open ditches for subsurface drainage, indicating water flow lines.

agriculture, environment and hydrology, as well as economic, social and socio-political aspects, in order to establish suitable criteria for optimal drainage [57]; however, the main purpose of drainage design is to ameliorate soils presenting water saturated layers. This improvement will be oriented towards soil conservation, as well as to optimize crop yield, to enable crops diversification and optimization of agricultural tillage operations using specific agricultural machinery. Adequate drainage system planning and design necessarily requires soil accurate studies, underground water origin and recharge rates, phreatic layer depth and time evolution, vertical water flow rates and crops characteristics related to soil profile water and salt contents [53] (Table 1).

Agricultural drainage studies require comprehensive data gathering, revision and analysis about geology, soil science, topography, wells, water level and its fluctuations, the amount, intensity and frequency of precipitations, superficial flow over the area to be drained, climatic characteristics and the phenology of crop productive development stages. A quantitative study relative to underground water dynamics under field conditions is also required, including information on water table positioning and its fluctuations throughout the crop production season, at various points within the region to be drained. These studies enable determining areas affected by drainage restrictions, defining the optimal distance and depth for lateral drains, and the flow to be removed, in order to sustain soil conditions suitable to crops development. There are two major drainage systems for controlling underground waters: open ditches (Figure 2) and subsurface piping (Figure 3). Open ditches systems consist of excavations in the soil that collect the water stored at existing saturated layers; it also can be used to remove surface run-off; this system can account for significant land farming losses, smaller soil units for farm machinery operation and interference with irrigation systems, making agricultural tasks more expensive [61,62]. Subsurface pipe drainage systems consists on plastic tubes, either smooth or corrugated, provided with perforations, that are placed buried within the soil, at specified distances and depths; this system is used mainly to lower the water table in the unconfined aquifers [54,63,64]. These drainage systems in most cases consist on a main drain, a collector drain and a network of field drain pipes; the position of the main drain depends on the field slope and the location of the lowest field level, through which the collected water is removed from the drained area. The collector drain and the network of field drains are usually located in parallel to each other; field drains are perforated pipes along their extension and its function is phreatic level control, by receiving water excesses present in the soil profile and convey this effluent towards the collector drain. Secondary drains and main drain main functions are water conductions from the drain pipes to the site of water discharge. These conductive drains are either open ditch type or underground pipes, the selected option will depend on costs and dimensions of piping [53, 54, 57, 60, 63, 64]. Subsurface drain design corresponds to a set of agronomic, hydraulic and engineering characteristics that a lateral drainage system must fulfill, to eliminate the volume of soil water required to satisfy crop optimal growth and production [1, 3, 65, 66]. In general, design features must define the proper criteria and parameters relevant to spacing among lateral drains, its depth placement inside the soil profile and the hydraulic characteristics of the hydraulic net, required to transport the water volume to be collected and removing it from the cultivated area. In relation to construction aspects, it must include definitions about drain hydraulic net layout, the materials to be used, the density and kind of perforations, as well as building techniques and network installation and maintenance.

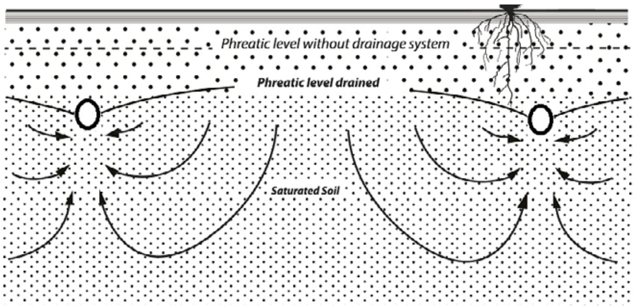

Figure 3: Underground pipes in sub-surface drainage, indicating water flow lines towards the drain pipe.

Optimal distance calculations between consecutive lateral drains are closely related to water flow towards the drains. The development of a mathematical model for quantitative description of the sub-surface flow towards lateral drains is possible only based on mathematical simplifications, deduced from the theory of underground water saturated flow, with pre-established initial and border conditions.

Conclusion

The normative and protocols established for agricultural land drainage in countries having expertise in the subject, have not been validated for the specific conditions of soils and situations of deficient drainage existing in local agricultural conditions. International standards for drainage networks specify the required properties for drainage materials (concrete, plastics and ceramics), as well as raw materials specifications, in terms of its chemical composition and the recommended additives. Also, very seldom specifications for drainage pipe resistance are available, as well as the proportions of recycled plastic as raw material allowance.

The existing norms for drainage materials proceeding from countries with a long drainage experiences might be used as a reference to define national standards, specifically needed for local circumstances. Optimization of perforation density and shape for PVC drainage pipe, allowing to increment water extraction efficiency and reducing pipe costs, is needed to define design and evaluation techniques of new components. A continuous, applied research program, carried on jointly by Universities, Research Institutes and Industry, can provide technologies to develop efficient and low cost drainage systems, adapted to local conditions.

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