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Guidelines and computer programs for the planning and design of land drainage systems

Cover photographs:
Drained lands of the Lower Guadalquivir Irrigation Scheme, Spain (left bank) and paddy fields with surface drainage systems (right bank). M.M. Ridao, Spain.

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AND
DRAINAGE
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- PC with Intel Pentium® processor and Microsoft® Windows 95 / 98 / 2000 / Me / NT / XP
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Foreword

Agriculture and, consequently, food production depend, among other factors, on the proper management of water. Land drainage, an integral component of water management, is well known to have ameliorated salinity and waterlogging problems in rainfed and irrigated agriculture. In so doing, it has contributed substantially to sustainable agricultural development through enabling increased crop production, decreased farming costs, and the maintaining of soil quality. In areas where rainfall is excessive, it is necessary to manage land drainage, both surface and subsurface, in order to prevent waterlogging. In areas where rainfall is deficient, drainage management is still important in order to minimize soil salinization.

In the arid and semi-arid regions, soil salinity still limits crop production significantly. Hence, it has a negative effect on food security. This is especially true in irrigated agriculture because of the salts added with the irrigation water and the buildup of saline groundwater where natural drainage is insufficient. Although only approximate figures are available, FAO estimated in 2002 that salinity had damaged about 20–30 million ha of irrigated land worldwide, and that 0.25–0.50 million ha were being lost from production every year as a result of soil salinization.

In the wetter regions, flooding and waterlogging still limit crop production in many parts of the world. In the inland valleys of sub-Saharan Africa with shallow groundwater tables, controlled drainage may help to increase crop production and improve the health of rural populations. In certain lands of the humid tropics, drainage is also needed in order to increase rice production and promote crop diversification. As the global population and the demand for food increase, additional new drainage systems will be installed in a broader range of climate, soil and hydrological conditions, and existing systems will be renovated.

FAO has already addressed waterlogging and salinity control through its normative and field programmes in the past 50 years. However, the context of land drainage has changed considerably in recent decades. This change has come about owing to concerns for the environment and the recognition of the need to integrate system users into the planning, design, operation and maintenance process. In addition, the experience gained and the research of recent years have led to improvements in the technology and methods.

This FAO Irrigation and Drainage Paper is intended to serve as a tool for an integrated drainage approach by providing guidelines for: (i) the appropriate identification of drainage problems; (ii) the planning and design of drainage systems; and (iii) the careful integration of technical, environmental and socio-economic factors.

The main text of this paper provides critical general information about the planning and design of land drainage systems and their relationship with technical, socio-economic and environmental aspects. The annexes provide more detailed information with technical background, appropriate equations, some cross-references for finding appropriate methodologies, and computer programs for applications developed by Professor W.H. Van der Molen, which are included on a CD–ROM.

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List of acronyms

CN	Curve Number
EC	Electrical conductivity
EIA	Environmental impact assessment
$FeSO_4$	Iron sulphate
GIS	Geographical information system
ICID	International Commission on Irrigation and Drainage
ILRI	International Institute for Land Reclamation and Improvement
IMTA	Mexican Institute for Water Technology
IWRM	Integrated water resources management
K	Potassium
KD	Transmissivity of soil layers
LAI	Leaf area index
M&E	Monitoring and evaluation
MSL	Mean sea level
N	Nitrogen
O&M	Operation and maintenance
P	Phosphorus
PE	Polyethylene
PVC	Polyvinyl chloride
R&D	Research and development
RS	Remote sensing
SAR	Sodium adsorption ratio
SCS	Soil Conservation Service
SEBAL	Surface Energy Balance Algorithm for Land
TDS	Total dissolved solids
UNEP	United Nations Environment Programme
USBR	United States Bureau of Reclamation
WHO	World Health Organization

List of symbols

Symbol	Description	Dimension
A	Cross-sectional area of drain (m^2)	L^2
	Surface area (m^2, ha)	L^2
	Basin area (ha)	L^2
	Area served per drain (km^2)	L^2
	Area served per well (m^2)	L^2
	Factor of the piezometer method depending on shape (cm)	L
A'	Reduced cross-sectional area of drain because of sedimentation (m^2)	L^2
A_8	Factor of the piezometer method for $H = 8d$ (cm)	L
a	Coefficient	-
	Conversion factor	-
	Blasius coefficient	-
	Distance to more permeable subsoil in interceptor drain (m)	L
a_c	Corrected coefficient	-
an_i	Anisotropy factor of layer i	-
an_1	Anisotropy factor of layer 1	-
an_2	Anisotropy factor of layer 2	-
B	Length of subsurface drain (m)	L
	Length of waterway in wind direction (km)	L
B'	Horizontal distance of subsurface drain (m)	L
B_c	Length of collector drain (m)	L
B_{i-1}	Begin of drain section (m)	L
B_i	End of drain section (m)	L
B_1	Length of first section in drain line with increasing diameter (m)	L
b	Bottom width of drainage channel (m)	L
	Width of drain trench or ditch bottom (m)	L
	Crest width in weir (m)	L
C	Constant	-
	Coefficient for surface runoff	-
	Installation cost of subsurface drainage system (US$/ha)	-
C_u	Cost per unit length of installed drains (US$/m)	-
c	Euler's constant	-
	Hydraulic resistance of semi-confining layer (d)	T
c_b	Entry resistance of drain (d)	T
D	Layer thickness (m)	L
	Thickness of aquifer (m)	L
	Average thickness of flow region (m)	L
	Depth of impermeable layer below bottom of auger-hole (cm)	L
	Distance to impermeable layer from piezometer cavity bottom (cm)	L
D'	Thickness of semi-pervious layer (d)	L
	Maximum initial thickness of flow region for numerical solution (m)	L
D_i	Amount of water interflows through topsoil (mm)	L
	Thickness of layer i	L

Symbol	Description	Dimension
D_r	Amount of subsurface drainage (mm)	L
D_s	Amount of surface drainage (mm)	L
D_0	Downstream thickness of flow in interceptor drain (m)	L
D_1	Average thickness of layer above drain level (m)	L
	Upstream thickness of flow in interceptor drain (m)	L
D_2	Thickness of layer below drain level down to impermeable subsoil (m)	L
	Thickness of first layer below drain level (m)	L
D_3	Thickness of second layer below drain level (m)	L
D_4	Thickness of third layer below drain level (m)	L
d	Thickness of equivalent layer (m)	L
	Inside drain diameter (m)	L
	Diameter of cavity in the piezometer method (cm)	L
d'	Thickness of semi-confining layer (m)	L
d_1	Diameter of first section in drain line with increasing diameter (m)	L
d_2	Diameter of second section in drain line with increasing diameter (m)	L
E	Amount of direct evaporation (mm)	L
	Actual evaporation from groundwater (md^{-1})	LT^{-1}
E_0	Potential evaporation from groundwater (md^{-1})	LT^{-1}
EC	Electrical conductivity (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
EC_e	Electrical conductivity of soil saturated paste (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
EC_g	Global electrical conductivity measured by remote sensing (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
EC_i	Electrical conductivity of irrigation water (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
EC_1	Initial soil electric conductivity (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
$EC_{1:2}$	Electrical conductivity in 1 to 2 soil solution (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
$EC_{1:5}$	Electrical conductivity in 1 to 5 soil solution (dSm^{-1})	$T^3I^2M^{-1}L^{-3}$
ET	Evapotranspiration (mm)	L
ET_c	Consumptive use during irrigation cycle (mm)	L
	Actual crop evapotranspiration (mm)	L
e	Base of natural logarithms	-
e_a	Irrigation application efficiency	-
F	Freeboard in open drain (m)	L
F_c	Calculation coefficient for corrugated pipes	-
F_s	Calculation coefficient for smooth pipes	-
Fr	Froude-Boussinesq number	-
F_1	Calculation coefficient for first section in drain line with increasing diameter	-
F_2	Calculation coefficient for second section in drain line with increasing diameter	-
f	Function	-
	Total correction factor for pipes with sediment	-
f_i	Leaching efficiency coefficient as a fraction of irrigation water applied	-
f_r	Leaching efficiency coefficient as a function of percolation water	-
f_1	Partial correction factor for pipes with sediment	-
f_2	Partial correction factor for pipes with sediment	-
G	Function	-
	Amount of capillary rise (mm)	L
g	Acceleration of gravity (ms^{-2})	LT^{-2}
H	Total allowed hydraulic head in drainpipe at design discharge intensity (m)	L
	Hydraulic head in aquifer (m)	L
	Depth of borehole below groundwater (cm)	L
	Depth of top cavity (piezometer method) below groundwater (cm)	L
H_x	Hydraulic head in drain at distance x (m)	L

Symbol	Description	Dimension
h	Horizontal	-
	Difference in basin elevation between most distant point and outlet (m)	L
	Hydraulic head midway between subsurface drains at design discharge (m)	L
	Total hydraulic head (m)	L
	Height of water column in auger hole (cm)	L
	Hydraulic head above crest level in weir (m)	L
	Total hydraulic head in pumping station (m)	L
h_a	Head in artesian aquifer above drain level (m)	L
h_c	Corrected hydraulic head considering anisotropy (m)	L
h_h	Hydraulic head for horizontal flow (m)	L
h_p	Hydraulic head in drainpipe in numerical solution (m)	L
h_s	Lift or static hydraulic head in pumping station (m)	L
h_r	Hydraulic head for radial flow (m)	L
h_t	Hydraulic head midway between subsurface drains at time t (m)	L
h_v	Vertical hydraulic head loss (m)	L
h_{ap}	Hydraulic head for approach flow (radial + entry) to the drain (m)	L
h_{des}	Design head for outflow system in numerical solution (m)	L
h_{init}	Initial hydraulic head in numerical solution (m)	L
h_0	Initial hydraulic head midway subsurface drains (m)	L
	Hydraulic head near drain in numerical solution (m)	L
h_1	Initial water column in auger hole (cm)	L
	Piezometer reading in tube laid midway between drains (m)	L
	Upstream water head in weir (m)	L
	Hydraulic head in first compartment in numerical solution (m)	L
	Hydraulic head in canal above original groundwater level (m)	L
h_2	Final water column in auger-hole (cm)	L
	Piezometer reading in a tube laid at some distance from drain (m)	L
	Downstream water head in weir (m)	L
	Hydraulic head in canal above drain level (m)	L
h_3	Piezometer reading in tube laid close to drain trench (m)	L
h_4	Piezometer reading in tube laid on the drainpipe (m)	L
h_{10}	Hydraulic head midway drains in numerical solution (m)	L
I	Gross irrigation depth applied at field level (mm)	L
	Rainfall intensity during concentration time (mmh^{-1})	LT^{-1}
I_a	Amount of water intercepted and infiltrated before overland flow (mm)	L
I_n	Net amount of irrigation water infiltrated into soil profile (mm)	L
I_{nf}	Accumulated infiltration into soil (mm)	L
	Infiltration rate (mmh^{-1})	LT^{-1}
i	Index for distance step in numerical solution	-
j	Index for time step in numerical solution	-
K	Basin constant (m)	L
	Hydraulic conductivity (md^{-1})	LT^{-1}
	Permeability of aquifer (md^{-1})	LT^{-1}
K'	Permeability of semi-confining layer (md^{-1})	LT^{-1}
K_h	Horizontal hydraulic conductivity of soil (md^{-1})	LT^{-1}
K_M	Reciprocal parameter of Manning's roughness coefficient ($m^{1/3} s^{-1}$)	$L^{1/3}T^{-1}$
K'_M	Corrected K_M coefficient ($m^{1/3} s^{-1}$)	$L^{1/3}T^{-1}$
K_v	Vertical hydraulic conductivity of soil (md^{-1})	LT^{-1}
K_{hi}	Horizontal hydraulic conductivity of layer i (md^{-1})	LT^{-1}
K_{vi}	Vertical hydraulic conductivity of layer i (md^{-1})	LT^{-1}

Symbol	Description	Dimension
K_1	Permeability above drain level (md^{-1})	LT^{-1}
	Permeability of topsoil (md^{-1})	LT^{-1}
K_2	Permeability below drain level (md^{-1})	LT^{-1}
	Permeability of first layer below drain level (md^{-1})	LT^{-1}
	Permeability of subsoil (md^{-1})	LT^{-1}
K_3	Permeability of second layer below drain level (md^{-1})	LT^{-1}
K_4	Permeability of third layer below drain level (md^{-1})	LT^{-1}
K_{2h}	Horizontal permeability below drains (md^{-1})	LT^{-1}
K_{2v}	Vertical permeability below drains (md^{-1})	LT^{-1}
L	Length (m)	L
	Drain spacing (m)	L
	Length of cavity (piezometer method) (cm)	L
	Well spacing distance (m)	L
L_c	Spacing of collector drain (m)	L
LF	Leaching fraction	-
l	Maximum distance in a basin between most distant point and outlet (m)	L
l_i	Length of section *i* of main drainage system (m)	L
m	Order number in data series	-
	Exponent	-
m_{50}	Median size of soil grains above 50 μm	L
N	Number of total data available in data series	-
n	Number of order	-
	Exponent	-
	Number of extremes in statistical analysis	-
	Coefficient in hill slope (v:h)	-
	Manning's roughness coefficient (sm$^{-1/3}$)	$T\ L^{-1/3}$
P	Amount of precipitation (mm)	L
	Probability	-
	Power (kW)	ML^2T^{-3}
P'	Amount of precipitation of equal duration in unit hydrograph (mm)	L
P_e	Effective precipitation (mm)	L
P_6	Amount of rainfall in 6 hours (mm)	L
P_{12}	Amount of rainfall in 12 hours (mm)	L
P_{24}	Amount of rainfall in 24 hours (mm)	L
P_{T1}	Precipitation for 1-year return period (mm)	L
P_{T5}	Precipitation for 5-year return period (mm)	L
P_{T10}	Precipitation for 10-year return period (mm)	L
pF	Decimal logarithm of soil suction expressed in cm	-
pH	Minus decimal logarithm of H^+ concentration	-
Q	Water flow, discharge (m^{3}s^{-1}, m^{3}d^{-1})	L^3T^{-1}
	Flow towards well (m^{3}d^{-1})	L^3T^{-1}
$\|Q\|$	Absolute value for Q (m^{3}s^{-1})	L^3T^{-1}
Q_M	Maximum discharge for return period equivalent to design rainfall (m^{3}s^{-1})	L^3T^{-1}
Q_w	Discharge of well, absolute value (m^{3}d^{-1})	L^3T^{-1}
Q_{in}	Flux entering an element per m^1 length (m^{2}d^{-1})	L^2T^{-1}
Q_{out}	Flux leaving an element per m^1 length (m^{2}d^{-1})	L^2T^{-1}
Q_2	Flux below drain level per m^1 drain (m^{2}d^{-1})	L^2T^{-1}
q	Specific discharge (mmd^{-1}, md^{-1}, ls^{-1}ha^{-1})	LT^{-1}
	Flux density to drain (md^{-1})	LT^{-1}
	Surface drainage coefficient (m^{3}s^{-1}km^{-2})	LT^{-1}
	Upward flow towards interceptor drain (m^{2}d^{-1})	L^2T^{-1}

Symbol	Description	Dimension
q_M	Maximum specific discharge (mmd^{-1} , md^{-1}, $ls^{-1}ha^{-1}$)	LT^{-1}
q_t	Specific discharge at time *t* (md^{-1})	LT^{-1}
q_0	Downstream flow per m length of interceptor drain (m^2d^{-1})	L^2T^{-1}
	Original outflow from canal (m^2d^{-1})	L^2T^{-1}
$\|q_0\|$	Flux to drain (absolute value) one-sided (m^2d^{-1})	L^2T^{-1}
q_1	Flux density above drain level (md^{-1})	LT^{-1}
	Upstream flow per m length of interceptor drain (m^2d^{-1})	L^2T^{-1}
	Outflow from canal after interceptor drainage (m^2d^{-1})	L^2T^{-1}
q_2	Flux density below drain level (md^{-1})	LT^{-1}
R	Amount of percolation water (mm)	L
	Amount of recharge (mm)	L
	Recharge by precipitation or irrigation excess (md^{-1})	LT^{-1}
	Hydraulic radius (m)	L
	Radius sphere of influence of well (m)	L
R^*	Long-term leaching requirement (mm)	L
Re	Reynolds' number	-
r	Effective drain radius (m)	L
	Radius of borehole (cm)	L
	Radius of piezometer protecting pipe (cm)	L
	Distance from well centre (m)	L
r^*	Distance centre of cavity to surface if $H/D > 8$ (piezometer method) (cm)	L
r_d	Distance from cavity well where spherical flow starts (m)	L
r_o	Radius of sphere equivalent to cavity for $H > 8D$ (piezometer method) (cm)	L
r_w	Radius of well (m)	L
r_8	Radius $8d$ beyond which flow is supposed radial (piezometer method) (cm)	L
S	Maximum potential retention in a basin (mm)	L
	Seepage (mm)	L
	Spacing of individual corrugations (m)	L
S_r	Excess of water at soil surface (mm)	L
	Surface runoff (mm)	L
S_r'	Surface runoff produced by precipitation *P'* in unit hydrograph (mm)	L
SAR	Sodium adsorption ratio ($meq^{1/2}l^{-1/2}$)	$M^{1/2}L^{-3/2}$
SDW	Sum of days with waterlogging during certain period (d)	T
SDW_{30}	*SDW* at less than 30 cm depth (d)	T
SDW_{50}	*SDW* at less than 50 cm depth (d)	T
s	Hydraulic gradient	-
	Hydraulic gradient for drainpipe flow	-
	Drain slope	-
s_x	Standard deviation in Gumbel distribution	-
T	Return period (years)	T
	Transmissivity (*KD*) (m^2d^{-1})	L^2T^{-1}
TDS	Total dissolved solids (gl^{-1})	ML^{-3}
t	Time (s, h)	T
	Average time of storm (h)	T
	Time base length of hydrograph (h)	T
t_c	Concentration time (h)	T
t_d	Lag time between average time of storm and time for maximum discharge (h)	T
t_e	Elevation time or time to peak (h)	T
t_r	Recession time (h)	T

Symbol	Description	Dimension
t_1	Initial time during time period (s)	T
t_2	Final time during time period (s)	T
u	Constant in Gumbel distribution	-
	Wetted perimeter (m)	L
	Wet circumference of drain (m)	L
v	Vertical	-
	Average flow velocity (ms^{-1})	LT^{-1}
	Wind velocity (ms^{-1})	LT^{-1}
v_d	Flow velocity at outlet of delivery pipe of pumping station (ms^{-1})	LT^{-1}
v_i	Average flow velocity in section i of main drainage system (ms^{-1})	LT^{-1}
v_M	Maximum average flow velocity (ms^{-1})	LT^{-1}
W	Total flow resistance near drain (radial + entry) (dm^{-1})	TL^{-1}
W_r	Radial flow resistance (dm^{-1})	TL^{-1}
W_{fc}	Moisture content at field capacity (mm)	L
x	Horizontal coordinate	-
	Distance (m)	L
	Distance from drain (upstream) (m)	L
	Values of extremes in Gumbel distribution	-
$\bar{x}$	Average value in Gumbel distribution	-
x_0	Limiting value in Gumbel distribution	-
Y	Relative crop yield	-
y	Vertical coordinate	-
	Water depth in drainage channel (m)	L
	Depth of water level below groundwater in auger hole (cm)	L
	Water level below groundwater in piezometer (cm)	L
	Reduced Gumbel variable	-
$\bar{y}$	Average value of y in interval where $y > 3/4y_0$ (auger-hole method) (cm)	L
y_0	Depth of water level below groundwater in auger hole at time 0 (cm)	L
y_1	Depth of water level below groundwater in auger hole or piezometer at time 1 (cm)	L
	Water depth in drainage channel at extreme discharge (m)	L
y_2	Depth of water level below groundwater in auger hole or piezometer at time 2 (cm)	L
	Water depth in drainage channel at design discharge (m)	L
Z	Drain depth (m)	L
Z_c	Collector depth below soil surface (m)	L
Z_r	Average thickness of rootzone (m)	L
z	Groundwater depth (m)	L
	Design groundwater depth midway between drains at design discharge (m)	L
$\bar{z}$	Average depth of the water table (m)	L
z_c	Critical groundwater depth where $E = 0$ (linear model) (m)	L
z_h	Critical groundwater depth where $E = 0.4343E_0$ (exponential model) (m)	L
z_i	Vertical distance of layer i (m)	L
z_0	Groundwater level observations in piezometer laid on drainpipe (m)	L
z_1	Salt content in rootzone at start of certain period ($mm.dSm^{-1}$)	$T^3I^2M^{-1}L^{-2}$
z_2	Salt content in rootzone at end of certain period ($mm.dSm^{-1}$)	$T^3I^2M^{-1}L^{-2}$
$z_{6.5}$	Groundwater level observations in piezometer at 6.5 m from drain (m)	L

Symbol	Description	Dimension
$z_{12.5}$	Groundwater level observations in piezometer at 12.5 m from drain (m)	L
z_{25}	Groundwater level observations in piezometer at 25 m from drain (m)	L
α	Constant in Gumbel distribution	-
	Coefficient	-
	Coefficient in side slope (*v*:*h*)	-
	Angle of slope (radians)	rad
γ	Angle (radians)	rad
φ	Angle (radians)	rad
η_p	Pump efficiency	-
η_t	Transmission efficiency in pumping station	-
θ_l	Minimum soil water fraction for non-crop stress (m^3/m^3)	-
θ_{fc}	Soil water retained at field capacity (m^3/m^3)	-
θ_{wp}	Soil water retained at wilting point (m^3/m^3)	-
κ_i	Transformed permeability of layer *i* considering anisotropy (md^{-1})	LT^{-1}
λ	Coefficient	-
	Characteristic length of aquifer (m)	L
μ	Coefficient	-
	Drainable pore space	-
$\bar{\mu}$	Average drainable pore space	-
ζ_i	Transformed vertical distance considering anisotropy (m)	L
π	3.1416…	-
ρ	Density of water (kgm^{-3})	ML^{-3}
τ	Lag time (d)	T
ν	Kinematic viscosity (m^2s^{-1})	L^2T^{-1}
Φ	Function	-
	Coefficient	-
Ψ	Coefficient	-
ΔH	Head loss in drain (m)	L
ΔH_i	Head loss in drain in *i* (m)	L
ΔH_1	Head loss in first section of drain line with increasing diameter (m)	L
ΔH_2	Head loss in second section of drain line with increasing diameter (m)	L
Δh	Head loss (m)	L
	Average fall of groundwater table in certain period of time (mm)	L
	Head difference along canal caused by wind (m)	L
	Head loss along culvert	L
	Available head in weir (m)	L
	Total head loss in suction and delivery pipes of pumping station (m)	L
	Difference in piezometric head above trench bottom of interceptor drain (m)	L
ΔS_r	Increment of surface runoff (mm)	L
Δt	Increment in time (s)	T
ΔW	Time-step (d)	T
	Change of the moisture content of rootzone (mm)	L
Δx	Distance step (m)	L
Δz	Variation of salinity in the short term ($mm.dSm^{-1}$)	$T^3I^2M^{-1}L^{-2}$

Chapter 1
Introduction

NEED FOR AND BENEFITS OF LAND DRAINAGE

Drainage of agricultural land is one of the most critical water management tools for the sustainability of productive cropping systems, as frequently this sustainability is extremely dependent on the control of waterlogging and soil salinization in the rootzone of most crops. On some agricultural lands, the natural drainage is sufficient to maintain high productivity. However, many others require improvements in surface and subsurface drainage in order to optimize land productivity, while maintaining the quality of soil resources. As time passes, drainage requirements may change because of changes in the general socio-economic conditions, such as input and output prices, and more intensive crop rotations.

In rainfed and irrigated areas of the temperate zones (where waterlogging is the dominant problem in lands lacking natural drainage), proper drainage has improved soil aeration and land and rural road trafficability. Moreover, it has facilitated the lengthening of the potential crop growth period.

In the irrigated lands of the arid and semi-arid regions (where salinity problems dominate), in addition to the benefits described above, subsurface drainage has been essential for controlling soil salinity and reducing the incidence of erratic crop yields.

In the semi-humid and humid tropical regions, drainage development has been less than in the agroclimate zones mentioned above. However, salinity control is required during the irrigation season in the semi-humid tropics, as is waterlogging control during the rainfall season (e.g. in countries with monsoon rainfall). In addition, flood control is also often a necessary component of drainage projects in many of these areas in order to protect the safety and livelihood of the rural population more effectively. In plains in the humid tropics, occurrences of organic soils or acid-sulphate soils often present special problems whose resolution entails careful drainage.

The general goal in all agroclimate zones is to obtain a proper water table control necessary at the given time and under the given circumstances. Sometimes, special water control methods are required, e.g. in acid-sulphate soils and in peat soils, and in areas where rice is grown in rotation with dry-foot crops.

CURRENT CONTEXT OF LAND DRAINAGE

Land drainage works usually have public (or semi-public) and individual farmers' components. Especially in developing countries, drainage projects deal with the former component and often take place in deltaic areas, coastal fringes and river valleys where population is increasing rapidly and land use is intensifying. Projects are prepared, carried out and financed under the responsibility of a standing government organization or a specific rural water authority. Completed projects are operated and maintained by the government organization in charge of managing the existing systems. However, increasingly, self-financing authorities and water users organizations with farmer participation are becoming legally involved in the implementation and financing of the necessary operation and maintenance (O&M) activities of the lower tiers of public irrigation and drainage systems.

Modern drainage system planning and design should take into account a wide range of agricultural and non-agricultural values and consider a broad group of stakeholders. The publication *Reclaiming Drainage, Toward an Integrated Approach* (World Bank, 2004) provides sound guidance for facilitating wider planning and design.

Much of the existing drainage installation work has been done in developed countries. While about 27 percent of the agricultural land in developed countries is provided with some form of improved drainage, only about 7 percent of agricultural land in developing countries is supplied with drainage (Smedema and Ochs, 1998). Therefore, there is room for drainage development in the latter countries, because land productivity has to increase dramatically in order to enable rural incomes to rise.

The context of land drainage has changed considerably in recent decades owing to changes in agriculture policies, mainly in developed countries, and to new environmental and natural resource considerations.

In developed countries, food security generally means quality of efficiently produced safe food, and environmental issues are becoming a first priority, jointly with maintaining the rural environment. Therefore, no substantial horizontal expansions of new drainage developments are foreseen in these countries, but only consolidation of the existing agricultural areas and the rehabilitation of and/or technological improvements to outdated existing drainage systems in line with the changed socio-economic circumstances. As there is a good background of drainage information in these countries, the transfer of expertise and the evaluation of the performance of existing systems may be the predominant activities as far as drainage is concerned.

In developing countries, food security means food availability, which is not achieved satisfactorily in too many countries. Consequently, the enhancement of agricultural production to raise rural incomes and the reduction of crop failure risks are still the main priorities, but on a sustainable basis.

In arid and semi-arid regions, irrigation development is still required in order to achieve food security. Therefore, to achieve the continuous benefits from irrigation projects, new or more intensive drainage systems will be needed to control waterlogging and soil salinity, and to ensure the sustainability of production on irrigated lands. This is especially the case in areas where irrigation water availability and water quality decrease owing to urban, industrial and environmental developments (Croon and Risseeuw, 2005). Drainage will also be required in order to reclaim salt-affected soils and problem soils if new lands are needed for agricultural use. In already drained lands, evaluation of the performance of existing drainage systems will also be needed in order to determine the need for rehabilitation.

In addition, the installation of new drainage systems in the humid tropics is expected in the near future. However, little practical experience is available in much of the humid tropics. In these areas, crop diversification (through the introduction of dry-foot crops in areas where rice fields are traditionally the major land use) will require subsurface drainage in addition to the existing surface drainage facilities. Agriculture intensification, by growing vegetables and tropical fruit trees, will also need subsurface drainage in areas lacking natural drainage. If in irrigated lands drainage is closely related to irrigation, in the flat areas of the humid and semi-humid tropics land drainage must be a component of integrated flood management.

Environmental issues are becoming more important and, therefore, they should be considered in the planning and designing of new drainage systems and in the rehabilitation of existing ones. Water quality control must also be considered. Moreover, opportunities for enhancement, reuse and protection of water are paramount for an intervention for drainage to be considered successful and supported by stakeholders and the community of concerned citizens adjacent to a project. When planning or designing drainage systems, consideration must also be given to any other locally important environmental matters, such as the protection and enhancement of wetlands and wildlife habitats, and to matters related to community health.

These changes have brought concerns for the environment, and the recognition of the important need to integrate users into the planning, design, operation and maintenance process, and financing of the capital and recurrent costs of land drainage systems. In addition, it is necessary to integrate irrigation, drainage and flood control with important agronomic, environmental and socio-economic aspects. Such integration is intended to provide a proper balance between sustainable agriculture and the environment in rural areas. With proper planning, drainage can also contribute to restoring or maintaining environmental values.

In addition to the previously described changes, improvements in the technology and methods applied in drainage development have been made as a consequence of the experience gained and the research carried out in recent years. For example, computers and computer-trained people are available even in remote rural environments, and remote-sensing technologies are becoming adapted to identify waterlogged and salt-affected areas.

NEED FOR GUIDELINES AND COMPUTER PROGRAMS FOR PLANNING AND DESIGN

A land drainage project is frequently a component of another agricultural water management project where drainage practices may be required, e.g. an irrigation project. Then, integration of the different components of the land and water project is especially essential. In the drainage component of such broad development projects, the following phases may be distinguished:

- identification, characterization and priority ranking of the problem areas;
- planning and designing of the systems;
- implementation and control of the quality of the works;
- O&M;
- evaluation of the performance of the system.

Through this process, many essential decisions must be taken at different government levels on proposals made by planners and designers.

This publication considers only the first two items, with the emphasis on the technical aspects. Nijland, Croon and Ritzema (2005) provide guidelines for the implementation, operation and maintenance of subsurface pipe agricultural drainage systems, including the assessment of the quality of the installed works. FAO (2005) has also published guidelines for selecting and designing the most appropriate drainage materials (pipes and envelopes) for land drainage systems. A future FAO publication will cover the evaluation of the performance of existing drainage systems.

Although up-to-date text books on land drainage exist, such as ILRI (1994), Skaggs and Van Schilfgaarde (1999), and Smedema, Vlotman and Rycroft (2004), specific and concise guidelines and user-friendly computer programs for drainage design calculations (based on simple and limited input parameters) may facilitate the work of field drainage engineers in planning or designing drainage facilities.

These guidelines are intended to serve as a tool for integrated drainage planning and design, giving due consideration to sustainability, and to environmental and socio-economic factors. Therefore, this publication is not a comprehensive handbook as such; rather, it presents new guidelines and calculation tools developed under the current land drainage context. It is oriented to engineers with previous drainage background. Readers who might not be familiar with some background theory are referred to the recommended handbooks and the references quoted in this publication.

IMPORTANCE OF FOLLOWING A PLANNING AND DESIGN PROCEDURE

The evaluation and integration of alternative solutions and comprehensive planning are critical to the success of drainage projects. Drainage is only one part of the solution, and careful consideration of potential alternatives is necessary where developing new areas or improving existing agricultural lands. Comprehensive planning in a river basin is critical, especially for large or numerous small projects. The drainage options should be weighed carefully along with the other water management alternatives in order to achieve the socio-economic development and environmental protection desired in any project area.

As there are many unknowns and assumptions in areas with little or no experience in drainage, a flexible approach is required early in the planning and design process. This is so that adjustments can be made as necessary in order to address unforeseen items encountered during the investigations or design problems that develop as the construction work is in progress. This means that, where part of the system has been implemented, the assumptions should be verified systematically by monitoring and evaluation (M&E) under the responsibility of a permanent institution. Where it is shown that the system does not fulfil all the expectations, the design criteria or the methods applied can still be adjusted before the remaining area is constructed. Thus, good design procedures will result in efficient, cost-effective and easily implemented drainage designs.

In this way, experience is built up, which can finally lead to fixed design procedures that are adapted to the prevailing circumstances. Such design procedures for drainage, as well as for most civil works, are complex. In drainage design, it is important to start with a well-prepared but flexible plan that is developed within a framework of public participation and sound consideration of alternatives. Environmental, social, economic, health and physical factors must be considered in preparing the designs. The participatory procedures used in planning cannot be discarded during the design process. They must be continued and made a part of the design procedure in order to ensure a sound follow-up so that stakeholders are satisfied. The resulting drainage water management system should be easy to operate and maintain in accordance with the needs of the area.

SCOPE OF THIS PUBLICATION

The concept of this FAO Irrigation and Drainage Paper is to focus on the "what to do and when" in the main text while including the technical details of the "how to do" in the annexes.

Chapter 2 provides general information about environmental considerations that should be taken into account in drainage projects in order to mitigate the unfavourable impacts of drainage development on the environment and enhance the positive ones. Chapter 3 deals with the socio-economic aspects that must be considered in the planning and design of agricultural drainage systems. Chapters 4–8 address the technical aspects.

In the planning and design procedure, different phases can be distinguished. These range from the identification of the problem lands of an agricultural area and their further characterization, to the assessment of the technical, socio-economic and environmental feasibility of the systems planned to solve the waterlogging and salinity problems. Once this feasibility has been confirmed, the design of the drainage works can be completed. For these purposes, the first step in the procedure is the collection of the necessary field information (climate data, topographic maps, soil and hydrological data, etc). According to the specific objectives of the procedure phase, fieldwork is done at different levels of intensity, and maps are prepared at different scales. Chapter 4 contains a description of this process.

Two complementary drainage systems are usually distinguished to control waterlogging and salinity, where drainage is not adequately provided by nature and by the existing watercourses: (i) individual surface and/or subsurface field drainage systems to remove excesses rainfall or irrigation water from the individual fields; and (ii) an open public main drainage system that collects the water from the field drainage systems and carries it to an outlet. Both systems must be constructed or improved in order to ensure adequate land drainage and soil salinity control.

The public main drainage system consists of an outlet for the drainage water (an open connection, outlet sluice or pumping station) and a network of open channels to convey the water from the fields to this point. Without this main drainage system, field drainage cannot work properly. For this reason, this main drainage system for rather flat areas is described first in Chapter 5.

Where the soils are permeable enough, and water levels in the main drainage system are maintained at an adequate depth, a wide-spaced drainage system may be sufficient to maintain properly deep groundwater levels in the whole area. In some cases, the main drainage system can provide the required drainage. However, even where the normal groundwater level remains deep enough during wet periods, water may remain on the ground surface or on poorly permeable layers at shallower depths, where it forms perched water tables. Under these conditions, downward percolation can often be improved by deep ploughing or subsoiling to break up hardpans and other types of less pervious soil layers. In some exceptional cases, a single operation is sufficient, but regular repetition is required in others.

If these measures are not successful, a field drainage system must be laid out in order to remove this surface water. The same is the case where the main drainage system fails to remove sufficient groundwater. Field drainage systems can consist of shallow open waterways to remove water standing on the soil surface, or deeper drains to control high groundwater tables and to discharge salts. The latter are usually buried pipe drains.

Surface drainage systems are needed where soil infiltration rates are low and rainfall or irrigation water ponds on the ground surface. Such low infiltration rates are usually caused by the formation of a surface crust, to which some soils are very susceptible. Stagnation of this kind is usually first noted in small depressions and at the lower borders of irrigation basins. The problem can be reduced by smoothing the land to remove small depressions and by providing the surface with a consistent non-erosive slope for excess water to flow through furrows or shallow field ditches towards surface drainage outlets. In very flat areas, bedding systems are applied to create strips with less waterlogging in between furrows, which convey excess surface water to the ditched field borders. Surface drainage water collected in these ways can be discharged through protected points into the larger watercourses of the main drainage system. Such surface drainage systems are described in Chapter 6, as are methods to estimate peak discharges, which are needed to design the different components of the drainage system.

Deeper subsurface drainage is needed to prevent high groundwater tables that lead to both waterlogging and soil salinization, of which the latter is the main consequence of high water tables in arid environments. Waterlogging is caused by rainfall, snowmelt and, in dry periods, excess irrigation water. The way its control is achieved depends on the causes of the problem. Where the surface drainage system is capable of removing excess water, but the groundwater table is still too high, the soil is not permeable enough for sufficient flow to the surface system. This is a common feature in plains and in some sloping lands, and it requires additional measures for field drainage.

Another cause of high water tables is seepage. This is the lateral movement of excess water from leaky irrigation canals or from higher ground elsewhere, or the upward flow coming from deep artesian aquifers. Such seepage can be controlled at the source (e.g. by canal lining), on its way (by interceptor drains) or at the field itself (by drains or wells). However, drainage of areas recharged by seepage is often difficult and costly. In severe cases, it is usually better to leave such areas as wetlands.

Groundwater control can be achieved by open drains, buried pipes and wells. The function of these hydraulic structures is to accelerate the removal of excess groundwater and to maintain the water levels in the soil at such depths that they do not harm crop production and soil workability. Moreover, they should provide sufficient downward movement of water to prevent the capillary rise and subsequent accumulation of salts in the topsoil and to evacuate the salt that has entered the field with the irrigation water. The former requirement is dominant in humid areas, the latter in arid environments.

The different methods of subsurface drainage have their advantages and disadvantages. Buried pipes do not have most of the drawbacks of open drains, i.e. loss of land, maintenance problems, obstruction of farming operations, and weed growth. However, they need to be installed properly and maintained in good condition by adequate cleaning. The frequency of cleaning depends on the local circumstances. While some soils cause hardly any clogging of the pipes, other locations show such rapid clogging (often by iron compounds) that the pipes must be cleaned each year. This combination of soil properties and cleaning operations will lead to a certain "maintenance status" varying from "excellent" to "poor", depending on the degree of clogging. Subsurface drainage with buried pipes forms the main subject of Chapter 7.

Public or individual vertical drainage systems driven by pumping wells can be used to lower the groundwater level under special hydrogeological circumstances, i.e. a good aquifer that has sufficient contact with the shallow groundwater. However, it is only economic where the water obtained can be used for irrigation or for municipal supply. Moreover, it has the drawback that pumping aquifers usually leads to unwanted mobilization of salts from deep subsoil layers, which may subsequently cause salinity damage to the environment. Chapter 7 also gives a short description of well drainage and its consequences.

Finally, Chapter 8 describes the computer programs developed for calculating the design parameters of subsurface drainage systems. These programs have also been included in the CD–ROM accompanying this FAO Irrigation and Drainage Paper.

The annexes of this publication provide more detailed information, including technical background and appropriate equations used in the computer programs.