

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

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IRRIGATION  
AND  
DRAINAGE  
PAPER

62

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## List of CD-ROM contents

Computer programs

Present publication

### System requirements to use the CD-ROM:

- PC with Intel Pentium® processor and Microsoft® Windows 95 / 98 / 2000 / Me / NT / XP
- 64 MB of RAM
- 50 MB of available hard-disk space
- Adobe Acrobat® Reader (not included on CD-ROM)
- Printout of results available by copying all programs to PC



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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.

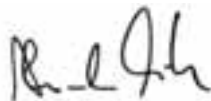
In the arid and semi-arid regions, soil salinity still limits crop production significantly. Hence, it has a negative effect on food security. This is especially true in irrigated agriculture because of the salts added with the irrigation water and the buildup of saline groundwater where natural drainage 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 <sub>4</sub>	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
<i>KD</i>	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)	$L$
	Thickness of semi-pervious layer (d)	$L$
$D'$	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 ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$E_0$	Potential evaporation from groundwater ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$EC$	Electrical conductivity ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_e$	Electrical conductivity of soil saturated paste ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_g$	Global electrical conductivity measured by remote sensing ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_i$	Electrical conductivity of irrigation water ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_1$	Initial soil electric conductivity ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_{1:2}$	Electrical conductivity in 1 to 2 soil solution ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$EC_{1:5}$	Electrical conductivity in 1 to 5 soil solution ( $\text{dSm}^{-1}$ )	$\text{T}^3\text{M}^{-1}\text{L}^{-3}$
$ET$	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 ( $\text{ms}^{-2}$ )	$\text{LT}^{-2}$
$H$	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
$l$	Gross irrigation depth applied at field level (mm)	L
	Rainfall intensity during concentration time (mmh <sup>-1</sup> )	LT <sup>-1</sup>
$l_a$	Amount of water intercepted and infiltrated before overland flow (mm)	L
$l_n$	Net amount of irrigation water infiltrated into soil profile (mm)	L
$l_{nf}$	Accumulated infiltration into soil (mm)	L
	Infiltration rate (mmh <sup>-1</sup> )	LT <sup>-1</sup>
$i$	Index for distance step in numerical solution	-
$j$	Index for time step in numerical solution	-
$K$	Basin constant (m)	L
	Hydraulic conductivity (md <sup>-1</sup> )	LT <sup>-1</sup>
	Permeability of aquifer (md <sup>-1</sup> )	LT <sup>-1</sup>
$K'$	Permeability of semi-confining layer (md <sup>-1</sup> )	LT <sup>-1</sup>
$K_h$	Horizontal hydraulic conductivity of soil (md <sup>-1</sup> )	LT <sup>-1</sup>
$K_M$	Reciprocal parameter of Manning's roughness coefficient (m <sup>1/3</sup> s <sup>-1</sup> )	L <sup>1/3</sup> T <sup>-1</sup>
$K_M'$	Corrected $K_M$ coefficient (m <sup>1/3</sup> s <sup>-1</sup> )	L <sup>1/3</sup> T <sup>-1</sup>
$K_v$	Vertical hydraulic conductivity of soil (md <sup>-1</sup> )	LT <sup>-1</sup>
$K_{hi}$	Horizontal hydraulic conductivity of layer $i$ (md <sup>-1</sup> )	LT <sup>-1</sup>
$K_{vi}$	Vertical hydraulic conductivity of layer $i$ (md <sup>-1</sup> )	LT <sup>-1</sup>



Symbol	Description	Dimension
$K_1$	Permeability above drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	Permeability of topsoil ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$K_2$	Permeability below drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	Permeability of first layer below drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	Permeability of subsoil ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$K_3$	Permeability of second layer below drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$K_4$	Permeability of third layer below drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$K_{2h}$	Horizontal permeability below drains ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$K_{2v}$	Vertical permeability below drains ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$L$	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 $50 \mu\text{m}$	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 ( $\text{sm}^{-1/3}$ )	$\text{T L}^{-1/3}$
$P$	Amount of precipitation (mm)	L
	Probability	-
	Power (kW)	$\text{ML}^2\text{T}^{-3}$
$P'$	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 ( $\text{m}^3\text{s}^{-1}$ , $\text{m}^3\text{d}^{-1}$ )	$\text{L}^3\text{T}^{-1}$
	Flow towards well ( $\text{m}^3\text{d}^{-1}$ )	$\text{L}^3\text{T}^{-1}$
$ Q $	Absolute value for $Q$ ( $\text{m}^3\text{s}^{-1}$ )	$\text{L}^3\text{T}^{-1}$
$Q_M$	Maximum discharge for return period equivalent to design rainfall ( $\text{m}^3\text{s}^{-1}$ )	$\text{L}^3\text{T}^{-1}$
$Q_w$	Discharge of well, absolute value ( $\text{m}^3\text{d}^{-1}$ )	$\text{L}^3\text{T}^{-1}$
$Q_{in}$	Flux entering an element per $\text{m}^1$ length ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$Q_{out}$	Flux leaving an element per $\text{m}^1$ length ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$Q_2$	Flux below drain level per $\text{m}^1$ drain ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$q$	Specific discharge ( $\text{mmd}^{-1}$ , $\text{md}^{-1}$ , $\text{ls}^{-1}\text{ha}^{-1}$ )	$\text{LT}^{-1}$
	Flux density to drain ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	Surface drainage coefficient ( $\text{m}^3\text{s}^{-1}\text{km}^{-2}$ )	$\text{LT}^{-1}$
	Upward flow towards interceptor drain ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$

Symbol	Description	Dimension
$q_M$	Maximum specific discharge ( $\text{mmd}^{-1}$ , $\text{md}^{-1}$ , $\text{ls}^{-1}\text{ha}^{-1}$ )	$\text{LT}^{-1}$
$q_t$	Specific discharge at time $t$ ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$q_0$	Downstream flow per m length of interceptor drain ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
	Original outflow from canal ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$ q_0 $	Flux to drain (absolute value) one-sided ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$q_1$	Flux density above drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	Upstream flow per m length of interceptor drain ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
	Outflow from canal after interceptor drainage ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$q_2$	Flux density below drain level ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
$R$	Amount of percolation water (mm)	L
	Amount of recharge (mm)	L
	Recharge by precipitation or irrigation excess ( $\text{md}^{-1}$ )	$\text{LT}^{-1}$
	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 ( $\text{meq}^{1/2}\text{l}^{-1/2}$ )	$\text{M}^{1/2}\text{L}^{-3/2}$
$SDW$	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 ( $KD$ ) ( $\text{m}^2\text{d}^{-1}$ )	$\text{L}^2\text{T}^{-1}$
$TDS$	Total dissolved solids ( $\text{gl}^{-1}$ )	$\text{ML}^{-3}$
$t$	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 ( $\text{ms}^{-1}$ )	$\text{LT}^{-1}$
	Wind velocity ( $\text{ms}^{-1}$ )	$\text{LT}^{-1}$
$v_d$	Flow velocity at outlet of delivery pipe of pumping station ( $\text{ms}^{-1}$ )	$\text{LT}^{-1}$
$v_i$	Average flow velocity in section $i$ of main drainage system ( $\text{ms}^{-1}$ )	$\text{LT}^{-1}$
$v_M$	Maximum average flow velocity ( $\text{ms}^{-1}$ )	$\text{LT}^{-1}$
$W$	Total flow resistance near drain (radial + entry) ( $\text{dm}^{-1}$ )	$\text{TL}^{-1}$
$W_r$	Radial flow resistance ( $\text{dm}^{-1}$ )	$\text{TL}^{-1}$
$W_{fc}$	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 ( $\text{mm.dSm}^{-1}$ )	$\text{T}^3\text{I}^2\text{M}^{-1}\text{L}^{-2}$
$z_2$	Salt content in rootzone at end of certain period ( $\text{mm.dSm}^{-1}$ )	$\text{T}^3\text{I}^2\text{M}^{-1}\text{L}^{-2}$
$z_{6.5}$	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
$\alpha$	Constant in Gumbel distribution	-
	Coefficient	-
	Coefficient in side slope ( $v:h$ )	-
	Angle of slope (radians)	rad
$\gamma$	Angle (radians)	rad
$\varphi$	Angle (radians)	rad
$\eta_p$	Pump efficiency	-
$\eta_t$	Transmission efficiency in pumping station	-
$\theta_i$	Minimum soil water fraction for non-crop stress ( $m^3/m^3$ )	-
$\theta_s$	Soil water retained at field capacity ( $m^3/m^3$ )	-
$\theta_{wp}$	Soil water retained at wilting point ( $m^3/m^3$ )	-
$K_i$	Transformed permeability of layer $i$ considering anisotropy ( $md^{-1}$ )	$LT^{-1}$
$\lambda$	Coefficient	-
	Characteristic length of aquifer (m)	L
$\mu$	Coefficient	-
	Drainable pore space	-
$\bar{\mu}$	Average drainable pore space	-
$r_i$	Transformed vertical distance considering anisotropy (m)	L
$\pi$	3.1416...	-
$\rho$	Density of water ( $kgm^{-3}$ )	$ML^{-3}$
$\tau$	Lag time (d)	T
$\nu$	Kinematic viscosity ( $m^2s^{-1}$ )	$L^2T^{-1}$
$\Phi$	Function	-
	Coefficient	-
$\Psi$	Coefficient	-
$\Delta H$	Head loss in drain (m)	L
$\Delta H_i$	Head loss in drain in $i$ (m)	L
$\Delta H_1$	Head loss in first section of drain line with increasing diameter (m)	L
$\Delta H_2$	Head loss in second section of drain line with increasing diameter (m)	L
$\Delta h$	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
$\Delta S_s$	Increment of surface runoff (mm)	L
$\Delta t$	Increment in time (s)	T
$\Delta t^*$	Time-step (d)	T
$\Delta \theta^*$	Change of the moisture content of rootzone (mm)	L
$\Delta x$	Distance step (m)	L
$\Delta z$	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.

## Chapter 2

# Environmental considerations in drainage projects

### INTRODUCTION

The results of the socio-economic benefits of creating conditions for sustainable agricultural production and reclaiming problem soils through land drainage are the increase in agricultural production through higher yields, the introduction of more rewarding crops and the obtaining of higher and less erratic farm income, in addition to a generally improved accessibility of the rural area and healthier living conditions.

Moreover, land drainage provides environmental benefits through the conservation and improvement of the quality of soil resources. In fact, irrigation development in arid and semi-arid regions without adequate drainage facilities has caused excessive salinization, resulting in extreme cases in severe deterioration of existing agricultural lands and making them unfit for agricultural production. Salinization is commonly reported as seriously affecting 20–30 million ha of the approximately 250 million ha of irrigated cropland. In addition, 250–500 000 ha are estimated to be lost from production every year as a result of salt buildup (FAO, 2002a). This area of salinization will grow if irrigation improvements to minimize water losses are not accelerated (Smedema and Ochs, 1998), and if the decreasing availability of good quality irrigation water in a number of important irrigated river plains and deltas in arid and semi-arid regions upsets soil salinity balances due to insufficient leaching (Croon and Risseuw, 2005).

Salinization is controlled by leaching excessive salts from the crop rootzone. This is the case where the net water movement in the soil over the year is downward and of sufficient magnitude to evacuate the accumulated salts. Where natural drainage in the soil profile does not achieve this, artificial drainage is required in order to provide a sustainable irrigated agricultural system. The salts requiring leaching are present in irrigation water and are also brought to the rootzone by capillary rise from high water tables, especially where the groundwater is salty.

The excessive seepage from canals, reservoirs and overirrigated farmlands also often contributes to groundwater recharge causing waterlogging, which can contribute greatly towards the need for artificial drainage systems. Judiciously minimizing irrigation water losses is a prerequisite to the installation of economically efficient drainage facilities.

Thus, land drainage can also have a favourable environmental impact as well-designed and implemented drainage systems can control soil salinization. At the same time, soil degradation and land desertification are avoided.

In some cases, already salinized lands can be reclaimed and brought back to their original or even better productivity through leaching, drainage and appropriate soil management. For this purpose, sufficient seasonal rainfall or irrigation water availability in combination with a drainage system is often required, which can serve for permanent salinity control after the reclamation. From an environmental standpoint, the lack of proper drainage in these areas results in farming systems that degrade, causing numerous socio-economic problems that may eventually lead to desertification.

In humid temperate zones, drainage systems can facilitate the management of groundwater levels according to an environmentally desired regime. Notably in arid and semi-arid regions, public drainage systems may facilitate the evacuation of polluted

drainage flows of urban and/or industrialized areas in order to avoid their mixing with fresh irrigation water supplies downstream.

In tropical areas, health problems are generally associated with vector-borne diseases, transmitted by insects that breed in stagnant water, and water-based diseases, transmitted by aquatic and semi-aquatic snails. Improvements in drainage conditions might have positive impacts on health if stagnant water is eliminated. In addition, lowering the groundwater table will facilitate sanitation and reduce the spread of diseases brought about by the absence or poor functioning of sanitation systems. Health issues related to drainage water management are described in FAO/ICID (1997).

However, drainage projects can have unfavourable side-effects on natural resources (soils and water) and on wetlands and the landscape. Potential negative environmental impacts of land drainage systems are numerous and include:

- Changes in hydrological peaks can affect downstream areas.
- The discharge of often saline drainage effluent can harm downstream areas.
- Soluble substances such as those causing eutrophication, remnants of pesticides and herbicides, and other pollutants or toxic substances (e.g. from urban and industrial areas) usually collect and concentrate in drainage water, notably in arid and semi-arid regions. They may enter the food chain through aquatic life and crops irrigated with drainage water.
- Disposal options for drainage water, such as evaporation ponds and outflow drains, and water treatment options, especially stabilization ponds and water desalination plants, can become sources of pollution and, thus, become hazardous.
- Banks of open drains can be eroded by water if they are not adequately designed and maintained. Moreover, even soils in flat areas can be eroded if surface runoff is not managed properly.
- Subsidence and irreversible desiccation of peat soils are common side-effects where such soils are drained improperly.
- Acid sulphate soils can form where lands of tropical swampy areas with soils rich in iron sulphate ( $\text{FeSO}_4$ ) are drained.
- The draining of lands adjacent to wetlands or higher-lying cropped areas can have negative effects on their groundwater levels.
- Straight layouts of the main drainage system can alter natural watercourses and have a negative impact on the riparian natural vegetation and the landscape.

As some of the above environmental matters are related to farming operations and water management at the field and project levels, the application of good agricultural practices is the first action to consider for reducing unfavourable impacts. However, water conservation and recycling within the project area and the safe disposal of drainage water must also be considered. Therefore, care must be taken to consider thoroughly the ramifications resulting from any drainage system changes. Improvements in the system designs and the construction of remedial structures or adoption of more suitable alignments of main drains may have considerable effects on downstream users. Basin-wide evaluations may be required in order to reach agreement on appropriate effective and sustainable control measures.

As both socio-economic improvements and environment enhancement should be the goal of drainage projects, potential conflicts between rural development and environment should be avoided, mitigated or resolved. Therefore, care must be taken in the planning, design, implementation, operation and maintenance phases of drainage projects in order to ensure that negative environmental impacts, once determined, are minimized to politically acceptable dimensions.

Major environmental impacts of irrigation and drainage projects and mitigation measures are described in FAO/ODA (1995). In addition, the International Commission on Irrigation and Drainage (ICID) prepared an “environmental checklist”

to assist in the identification of environmental effects of irrigation, drainage and flood control projects (ICID, 1993). This chapter focuses on the environmental aspects that should be considered in drainage planning and design. The following section discusses these issues briefly. Other aspects that can be controlled by management, especially concerning drainage water, have been considered in depth by FAO in other publications (FAO/ICID, 1997; FAO, 2002b).

## ENVIRONMENTAL PROBLEMS

### Changes in hydrological peaks

With time, hydrological changes in outflow can have negative or positive impacts downstream and can cause environmental concerns. The planning and design process must identify these potential changes from present conditions and their consequences. For example, in humid tropical and monsoon areas, the flood control and drainage component of planning and design are strongly interrelated. In these cases, main drains are usually multipurpose channels for flood control as well as for drainage water disposal, and they are sometimes used as irrigation canals in the dry season. Climate changes also influence the environment either directly or via changes in water flows.

### Water quality management

As a water development project generally causes changes in water quality both inside the area and downstream, water quality control is an essential factor to be considered in drainage planning and design. At the outlet of the system, drainage water quality influences the receiving water, usually in a negative way. Attention is needed for downstream water intakes for irrigation, municipal water supplies, nature reserves and wildlife habitats, which may be extremely sensitive to water pollution. The choice of a place to discharge drainage water is a crucial decision in the process of water quality control.

In arid zones, in addition to many possible different pollutants, the salt content of drainage waters is a main cause of concern because soil salinity control is necessary and the leached salts are discharged through the subsurface drainage system. Salinity control is needed to prevent secondary salinization of soils caused by the salts added with the irrigation water or the salts accumulated in the rootzone through capillary rise of saline groundwater. Irrigation development in arid zones can also lead to mobilization of primary salts present in soils, subsoils and deep strata. This process should be avoided as much as possible because salt mobilization, in conjunction with diminished river flow resulting from water diversions for irrigation, leads to increasing salinity of river waters. Smedema and Shiati (2002) have described in detail the principal salt mobilizing mechanisms and irrigation-induced river salinization with some examples from India and the Islamic Republic of Iran.

To provide quantitative information on the salt content of drainage water, Table 1 shows average values of electrical conductivity (EC) and total dissolved solids (TDS) in drainage waters.

In some areas, drainage water with high levels of toxic trace elements, such as boron and selenium, might cause environmental problems. Suspended sediment in surface runoff is another water quality factor to consider.

Therefore, analysis of the soils and the present groundwater quality

TABLE 1  
Classification of waters

Type of water	EC (dS/m)	TDS (g/litre)	Water class
Drinking and irrigation water	< 0.7	< 0.5	non-saline
Irrigation water	0.7–2.0	0.5–1.5	slightly saline
Primary drainage water and groundwater	2.0–10.0	1.5–7.0	moderately saline
Secondary drainage water and groundwater	10.0–25.0	7.0–15.0	highly saline
Very saline groundwater	25.0–45.0	15.0–35.0	very highly saline
Seawater	> 45.0	> 35.0	brine

Source: Adapted from FAO, 1992b.

must be made, as well as of the expected seepage water that may have a great influence on the future drainage water quality. The soils, for example, will lose most of their soluble salts within a few years, but seepage is a continuous process. If the seepage water is highly saline, a small amount will carry large quantities of salt into drains within the project area. This in turn will have a profound influence on the downstream water quality.

Generally, salinity is not a major problem in temperate regions. However, pollution from agricultural chemicals and in some cases manure applications requires careful control in spite of the fact that pollution tends to be diluted by frequent rainfall excesses, which is not the case in arid and semi-arid regions. Nitrogen (N), phosphorus (P) and pesticide residues are the major elements of concern. Considerable guidance on this subject has been provided by FAO (1996).

Therefore, while salt is a major concern in drainage water reuse in downstream agriculture, there are many other substances to be considered, such as:

- Domestic and agricultural wastes that may cause anaerobic conditions in the receiving waters. They are subject to a rapid biodegradation where enough oxygen is available, but this is not the case in almost stagnant water.
- Residues from manure, fertilizer and biodegradation of organic wastes in the water, mainly nitrates and phosphates, are favourable to agriculture, but they may cause algal blooms, rapid growth of aquatic weeds and ecological disturbances in downstream waters.
- Soluble toxic substances of natural origin. They occur in alluvial soils in some regions and are concentrated by reuse of the water and by its evaporation. Examples are: arsenic and fluoride in some groundwaters, making them unsuitable for drinking, boron in areas influenced by volcanism (toxic to fruit trees) and selenium in other regions (toxic to wildlife). Many of these elements are necessary for life in small quantities, but they may be present at dangerously high levels in some areas.
- Insoluble toxic substances of natural origin, such as heavy metals. They are almost absent in clear water, but they are adsorbed to suspended silt and clay and concentrated in bottom sediments from where they may move downstream in times of high discharges. Some processes can mobilize these adsorbed substances, after which they can become further concentrated through bio-accumulation.
- Residues from soluble and persistent pesticides, which endanger safe use of water for consumption by humans and animals. Persistent insoluble pesticides behave in much the same way as heavy metals.
- Single-celled organisms, bacteria and viruses that cause water-borne diseases. They are especially dangerous in drinking-water (where they can cause diseases such as cholera and typhus), while other species can spread human and plant diseases via the irrigation water (bilharzia, brown rot in potatoes, etc.).

In addition to controlling surface water quality, care must be taken that polluted waters do not reach deep freshwater aquifers that are used or may be used for municipal water supply. Unconfined aquifers and semi-confined ones with hydraulic heads below groundwater are vulnerable to such pollution. Where the aquifers are unconfined, saline water leakage from evaporation ponds, used for drainage water disposal, will move downward rapidly owing to its higher density. However, where the drainage water quality is good, recharge of aquifers may be beneficial. Designed recharge areas may even be appropriate in such a case.

Thus, the quality and quantity of water that may seep and cause recharge must be considered. However, in all cases, monitoring is critical to see that certain changed conditions do not create unexpected effects on the environment or groundwater resources.

**Soil conservation**

Even in flat areas, soil erosion by surface runoff is a potential risk, in particular at the outlets of the field surface drainage systems. The banks of open ditches are especially sensitive to water erosion where they are not covered by protecting natural vegetation. In addition to soil losses caused by erosion, the sediments transported by surface water are deposited in the system of open drainage channels, thereby reducing their hydraulic capacity.

Therefore, when designing and maintaining surface and subsurface drainage outlets, soil conservation measures must be considered in order to ensure the safe discharge of drainage water flowing from the field systems. Where singular drainage systems are used, the banks of the open ditches should be designed with an appropriate slope and be protected by natural vegetation. In arid zones, it is often difficult to maintain adequate plant cover (a reason for preferring composite drainage systems with subsurface pipe collectors). In this case, maintenance considerations concern primarily the main channels, especially at the outlets of these collectors.

**Wetland and wildlife habitat areas**

Existing valuable ecosystems must be respected where new systems are being built or additions made to existing projects. Important habitat lands are of worldwide concern and potential damages are numerous. Changes in existing water tables or in land use, and the pollution of wetlands, lakes and/or streams by disposed drainage water, can lead to loss of typical vegetation and fauna in nearby nature reserves or natural areas.

These ecological risks and opportunities entailed by drainage projects should be identified by environmental impact assessments (EIAs). Environmental plans should also discuss the protection and mitigation measures to be taken and formulate the works required to best protect these areas from negative influences or to enhance their existing quality. As many aspects considered in EIAs are not the direct competence of the drainage engineer, proper environmental specialists should assist in these efforts.

**WATER CONSERVATION AND RECYCLING WITHIN THE PROJECT AREA**

Management to control any drainage-related environmental problems must occur throughout the water development scheme and should not be confined only to the disposal point. The most efficient way to control water quality is to minimize the initial pollution from each field as the cumulative impacts are much more difficult and expensive to handle. Therefore, in order to prevent damages downstream from the outlet of the drainage system, a major effort must be made to minimize the degradation of water within the project area through sound field and farm water management.

In order to optimize agricultural production as well as to minimize pollution, farming practices should be in harmony with sound agronomic principles, such as the use of integrated pest management systems and controlling the use of fertilizers so they are provided as the plants need them. In addition, irrigation practice should prevent soil erosion. Therefore, care must be taken to prepare farmers to consider water quality impacts resulting from their operations. Irrigation and drainage designs must be compatible with the farming operations anticipated.

Inside the project area, management of drainage waters includes water conservation measures at the field level and reuse of drainage water at the farm and scheme levels where possible. These measures imply use of environmental criteria for adequate planning and design of drainage systems. However, there are often some practical complications, such as the implementation of a sound salt management system, which is required in arid and semi-arid zones in order to control soil salinization and degradation. These measures are sometimes difficult to implement because they require considerable management and discipline of the farmers.

At the field level, the main objective is to reduce the volume of drainage water and the salt and pollutant load discharged through the field drainage systems. This can be achieved by reducing surface runoff and deep percolation in the irrigated fields through improving on-farm irrigation management and by shallow water table management. Additional measures at the scheme level are reuse of drainage water, groundwater management, land retirement and dry drainage, and biological drainage. These measures are described briefly below. Additional detailed information is provided by FAO/ICID (1997), FAO/IPTRID (2002) and FAO (2002b).

Conservation and recycling of water within the project area will reduce the amount of drainage water to be discharged. However, this will be at the expense of its quality as salts, plant nutrients and other soluble substances will become more concentrated. The quantity of outlet water to be managed will be lower, but its quality will deteriorate. However, the amounts of persistent soluble pollutants discharged from the project area will remain almost the same unless they are reduced at the source, i.e. at field level. Therefore, field water management and sound crop husbandry practices are essential factors in controlling the quality of drainage water.

### **Improving on-farm irrigation management**

Increasing the irrigation efficiency within the project area may reduce the amount of drainage water to be disposed of. Sound irrigation application is necessary in order to reduce surface runoff water losses. Deep percolation can be reduced if the amount of irrigation water applied effectively and uniformly only covers crop water requirements plus the leaching fraction necessary to control soil salinity.

In many irrigation schemes, there is room to improve irrigation water conveyance and application efficiency by:

- improving local and regional scheduling of irrigation supplies;
- improving the irrigation practice in order to eliminate surface runoff;
- ensuring uniform water application over all the field;
- adjusting the irrigation requirements to the actual evapotranspiration needs considering the soil moisture storage capacity, while ensuring the annual leaching requirement for salinity control;
- making optimal use of rainfall in the annual salt/water balance in order to reduce irrigation applications in the drier part of the year;
- improving the existing surface irrigation systems;
- changing to pressurized systems, such as sprinkler or drip irrigation.

While upgrading the irrigation management to save water, care should be taken to ensure a minimum leaching fraction to wash out the salts applied with the irrigation water. Moreover, in arid and semi-arid regions, continued availability of relatively fresh drainage water flows (stemming from inefficient irrigation practices in upstream areas) is gaining importance in an increasing number of downstream areas (tail ends) within contiguous irrigated perimeters (Croon and Risseeuw, 2005).

As soil salinity control is a key environmental factor, Annex 7 provides details on leaching requirements.

### **Shallow water table management**

Where high water tables have relatively fresh water near the surface layers, as usually happens in humid areas, and soils are sufficiently pervious, water table levels can be managed to minimize drainage water quality problems before the water reaches a disposal point (water table management systems can also be used with less pervious clay soils but the risks and difficulties are greater). Specifically, water table management can contribute greatly towards the control of nutrient and pesticide pollution. A controlled high water table can also reduce the need for irrigation, thus saving freshwater for use elsewhere.



A shallow groundwater table can be maintained at different design depths if the water levels and the drainage discharge are controlled artificially, a technique known as controlled drainage. In dry periods, the drainage discharge is restricted and the groundwater level is kept close to the bottom of the rootzone. Thus, crops can benefit from groundwater supplied by capillary rise between the subsurface drains. In the wet season, the drainage system provides full discharge in order to maintain the water table low; thus, adequate aeration is achieved in the rootzone.

To prevent an excessive drawdown of the water table in the dry season, a constant supply of freshwater is required to replenish the soil water lost through crop evapotranspiration. Sometimes, a continuous supply by seepage maintains a sufficiently high water table if drainage is controlled. However, in the absence of natural seepage, the water table can be recharged by surface water conveyed through the main drainage system. To facilitate the water inflow into the soil through the subsurface drainage system (subirrigation), water levels in the collector system must be kept at a high constant design level. This is necessary in order to ensure sufficient hydraulic gradient to move water from the drains to the subsoil.

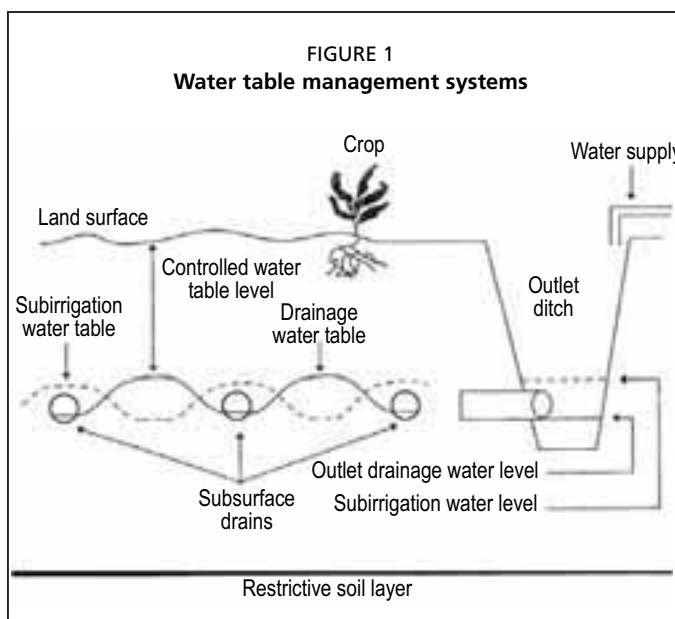
Water table management systems, as depicted in Figure 1, involve controlled drainage structures such as:

- plugs and elbows at the lateral outlet in singular drainage systems or at the collector outlet in composite drainage systems;
- water-level control weirs in the open main drainage system;
- automatic systems to control the water level in the pumping facilities.

Detailed designs for controlled drainage structures have been described by FAO (2005).

The quality of the groundwater is a key issue in water table management. Particularly in arid climates, maintaining a shallow groundwater table (with the exception of rice) can be very dangerous owing to the associated salinity hazard. If the groundwater is saline, salts transported by capillary rise will accumulate quickly in the rootzone. Therefore, such systems should not be considered unless the land is cropped permanently (e.g. the Nile Valley and Nile Delta). In areas where the accumulated salts can be leached by excess rainfall in the rainy season, e.g. in monsoon climates, or by surface irrigation after harvesting, care should be taken during the irrigation season to maintain soil salinity below the crop salt tolerance threshold.

Valuable research work has been developed on water table management. However, applying the results of research also requires judicious public water management capabilities. This task is frequently not easy and there are often conflicts, for example, where the available heads to infiltrate water are too small to be of practical use. On the other hand, if drainage is interrupted before the end of the rainy season and the drain base rises, by maintaining high water levels in the open drains, undesirable waterlogging can occur. Therefore, farmers sometimes prefer to pump the drainage water from the open drains during drought periods (as described below).



Source: FAO/ICID, 1997.

TABLE 2  
Quality of drainage water for use in irrigation

Quality	EC (dS/m)	Application
Very good	< 1	all crops
Good	1–2	most crops
Moderate	2–3	tolerant crops
Poor	3–6	tolerant crops, with ample leaching
Very poor	> 6	not recommended

### Drainage water reuse

In the tail ends and fringes of an increasing number of irrigated areas in arid and semi-arid regions, where freshwater supplies are also required for other socio-economic developments, medium-quality water from open drainage channels can potentially be used for irrigation.

Nowadays, drainage water is

necessarily used for irrigation, either directly or after mixing with irrigation water of better quality, in order to compensate for decreasing freshwater flows.

The suitability of drainage waters for reuse depends greatly on the salts and pollutants carried by the water, on the crops to be grown and on irrigation practices. Table 2 gives an indication of the salt content of waters, measured as EC, in relation to their suitability for irrigated agriculture.

Waters with a low salinity can be reused for irrigation by pumping directly from the open drains. Where N compounds are present, they can be beneficial for crops as they form a valuable nutrient input resource and can result in reduction of fertilizer cost. However, excess nitrates prevent their use for other purposes, such as drinking-water for humans or livestock. This is particularly the case where the water is also polluted with agrochemicals such as pesticides and/or raw sewage water and process water spills of urban and industrial areas.

At higher salt content and/or pollution levels, drainage water may be blended with freshwater to provide an acceptable irrigation water quality. Another option is to use freshwater in periods when crops are salt sensitive and to use more saline drainage water when they are tolerant. As plants are generally relatively sensitive during germination and emergence, but become more tolerant during later stages of growth, it is imperative to keep salinity in the seed bed low at these early stages. However, problems of soil structure stability can occur if freshwater is applied after irrigation with drainage water with a high sodium content. The cycling option requires special infrastructure and considerable public water management efforts in order to realize it on a practical scale.

As the drainage water quality is reduced owing to increased salinity, more salt-tolerant crops must be used. FAO (2002b) provides data prepared by Maas and Grattan (1999) on the relative salt tolerance of various crops at emergence and during growth to maturity. To verify whether a water of a certain salinity can be used safely for a particular crop, an annual salt balance can be made to check that the salt in the soil profile does not accumulate or rise periodically above the acceptable salt level chosen for the crop.

Saline (not polluted) drainage waters can also be used to:

- irrigate halophytes where a proper system for salinity control is provided;
- maintain water levels in commercial fish ponds;
- secure temporarily minimum water levels in environmentally valuable brackish coastal end lakes;
- provide leaching for reclamation of salt-affected soils during the initial stage of the reclamation process.

Large volumes of drainage water, which are not suitable for the irrigation of dry-foot crops, may be used successfully for continuous refreshment of the standing water layer of rice grown on non-subsurface drained clay soils in the tail ends of the irrigation system of the Nile Delta, Egypt. Rice yields on lands with a topsoil salinity in the growing season of 3–5 dS/m increased by about 1 tonne/ha if frequent flushing of the standing water layer decreased the average salinity of the standing water layer with 1 dS/m (Egyptian–Dutch Panel for Land Drainage, 1977–79).

Reuse of drainage water inside a project area reduces the volume to be disposed of, but tends to concentrate salinity and pollutants although the total load of discharged pollutants may be slightly reduced. Ultimately, disposal of this reduced volume of drainage water outside the project area is inevitable.

In the case of domestic or industrial wastewater polluting agricultural drainage water, degradable and notably persistent organic pollution is a major problem, and water treatment is needed in order to achieve safe reuse. For irrigation of crops not used for direct consumption, treated wastewater can be used directly. For this purpose, treatment by conveying the water through constructed wetlands with reeds or rushes, or through stabilization ponds, is often sufficient. However, for most other purposes, especially for irrigation of vegetables, more sophisticated methods of treatment are required. This subject has been covered by FAO (1992a and 1997).

More details on drainage water reuse can be found in FAO (1985, 2002b) and FAO/ICID (1997).

### **Groundwater management**

Pumping groundwater from tubewells can be an effective method for controlling waterlogging and salinity and it is widely used, e.g. in Pakistan. In freshwater areas, drainage wells are particularly valuable as the pumped water can be used for supplemental irrigation. Where the water pumped is slightly saline and cannot be blended with adequate quantities of fresh irrigation water, its reuse is seldom attractive. This is because the recycling of the saline water will gradually increase salinity levels in the soil and aquifer, thus causing the pumped water to become gradually more concentrated. Where the groundwater is salty, pumping a waste product is not economic unless there is a direct and safe disposal option.

Although often initially successful, tubewell pumping can result in upconing of saltwater from great depths, causing complex problems with irrigation and safe drainage water disposal. Therefore, it is important to consider the hydraulics of the deeper layers from which salts might be mobilized. A special construction of the wells (skimming wells) or double pumping of deep salty and shallow freshwater could prevent such upconing. However, sophisticated O&M practices are required. Moreover, with double pumping, the salty water discharge presents a new disposal problem. Systematic monitoring is a critical component for tracing water quality changes. Where such changes occur, adjustments in pumping rates are required in order to maintain a sustainability outlook. Therefore, subsurface horizontal pipe drainage should ultimately be considered in such areas as it will improve project sustainability and reduce the saltwater disposal problem considerably.

Chapter 7 provides technical details about vertical drainage.

### **Land retirement and dry drainage**

In new irrigation developments, environmental side-effects from salt and trace-element mobilization might be largely avoided if areas with saline soils and soils rich in those elements are not irrigated. In existing projects, lands can be taken out of production (retired) for the same reasons, especially if substituted by newly irrigated land without such sustainability risks.

Dry drainage is a questionable concept involving the creation of sink areas of fallow land, e.g. uncultivated strips between cropped lands. These function as evaporation basins, drawing a flux of water and salt from adjacent irrigated crop fields. This already occurs spontaneously in salt-affected areas where abandoned agricultural fields act as salt sinks and in nature, for example in low-lying fringe lands of alluvial fans and deltaic areas situated in arid zones, such as in the Tunuyan fan in Mendoza, Argentina, the Garmsar area in the Islamic Republic of Iran, the Indus Plain in Pakistan, and Mesopotamia in Iraq.

A dry-drainage water disposal system has potential in areas where land is abundant and water is too limited to irrigate all the lands serviced by an irrigation system. It also has potential in cases where drainage outlets are not available (Gowing and Wyseure, 1992). However, dry drainage might have negative impacts on the surroundings if the barren salinized land causes saline dust storms or flooding with saltwater of the adjacent lands during a rare heavy rainstorm. Furthermore, deep aquifers may be affected by density currents. Therefore, retired and fallow lands should be managed properly with adequate salinity control by public or semi-public water management organizations, which can secure a sustainable form of land use, such as halophyte development for fuelwood production or nature protection.

### Biological drainage

Biological drainage (biodrainage) is a concept based on plant evapotranspiration where tree belts are planted to remove excess soil water. Trees can absorb water from the unsaturated zone, thus diminishing deep percolation and subsequent recharge of the groundwater. They can also absorb water directly from the capillary fringe of the saturated zone. Thus, by lowering the groundwater level below their rootzone, lateral seepage can be intercepted or groundwater flow can be enhanced, and the water table of adjacent arable lands can be maintained at a depth suitable for crops. For biodrainage, highly evaporative plant species are recommended, such as some *Eucalyptus* varieties (Diwan, 1997), and in saline environments, salt-tolerant trees or shrubs, such as *Tamarix*.

In biodrainage systems, tree belts are planted systematically in different arrangements, according to the specific water control purposes:

- in areas with a deep water table to reduce percolation and recharge and thus prevent the rise of the water table;
- along a slope to intercept lateral seepage from highlands to lowlands;
- along irrigation canals to intercept lateral seepage due to leakage;
- in flat areas with a parallel layout similar to a subsurface pipe drainage system.

In dry lands where the water table is deep, tree plantations may be particularly useful to reduce recharge and be sustainable if the natural salt balance is not altered. In lands with subsoils rich in salts or harmful trace elements, the reduction in percolation can be especially useful by preventing their mobilization. However, as the introduction of non-native plants (especially of invasive species) may have a negative impact on the landscape, careful selection of the tree species is required.

Under certain conditions, tree belts can be effective at intercepting lateral seepage in sloping lands, and especially along irrigation canals, depending on the seepage amounts and the salt content of the canal water. However, the environmental impact on the landscape mentioned above should be considered. In addition to this, there may be risks of additional leakage from the canal as the hydraulic gradient increases owing to the lowering of the water table. Therefore, detailed benefit/cost analyses are recommended in order to compare the biodrainage option with other engineering alternatives, such as lining the canal or installing an interceptor drain.

Biodrainage systems may contribute to controlling waterlogging, while reducing the volume of drainage water to be disposed of by conventional drainage systems. However, they may not provide the long-term salinity control needed in arid climates, especially in irrigated lands. Salinity control is especially needed where the groundwater is shallow and saline, and salt buildup around the rootzone is inevitable. In this case, salts accumulated must be leached and conventional subsurface drainage systems may be required. As soil water salinity increases, plant evapotranspiration diminishes and the effect of biodrainage is reduced. In addition to these constraints, parallel tree layouts in flat irrigated lands to control shallow water tables may often be limited by the availability of land, which is generally scarce in irrigation schemes.

In summary, rootzone salinity control is critical in cropland areas served by such biological drainage systems. Careful design and management are essential as seepage rates, natural and artificial leaching, water availability, tree uptake efficiency, and maintenance can provide significant swings in effectiveness from season to season and year to year.

FAO/IPTRID (2002) have provided details on designing biodrainage systems and issues related to their implementation. This publication, which is based on several case studies, describes trends for future research and development (R&D) to address the current uncertainties mentioned above.

## **DRAINAGE OUTLET AND DISPOSAL TO AVOID OR MINIMIZE DOWNSTREAM EFFECTS**

### **General remarks on outlet structures**

The drainage water outlet is a critical point in any project, both from a viewpoint of downstream water quality and for the functioning of the project itself, because any flow stagnation in the conveyance channels causes problems upstream. Therefore, attempts must be made to prevent erosion and not locate outlet structures at points where heavy siltation may be expected. Moreover, the adverse downstream negative impacts on water supplies, fish, riparian habitats, wetlands and other valuable ecosystems must be minimized.

In some areas, particularly in humid and tropical zones, hydrological changes within the river system can also cause concerns related to the increase in flooding incidence or significant changes in base flows. Thus, river system hydrology related to some projects or groups of proposed projects requires hydrological evaluation.

This section considers only environmental aspects concerning the drainage outlet and disposal. Chapter 5 considers aspects of technical design, such as required levels and head differences.

In the planning phase, it is necessary to assess the volume and quality of the drainage effluent and the effects it will have on the downstream water systems. Considering the merits and drawbacks of alternative disposal routes, it must then be judged whether they are acceptable or not. On this basis, plans for remedial or mitigating measures must be formulated. Later in the design phase, the detailed environmental plan required for the selected disposal routes may be prepared.

Drainage water from the project must be disposed of in a safe way. Generally, it flows to the sea and tidal waters, to a lake or to a river.

Other possibilities for disposal of drainage water to minimize adverse impacts on downstream water resources are:

- evaporation ponds;
- constructed wetlands and related systems;
- the groundwater through recharge wells.

Each option has its advantages, drawbacks, problems and complications.

### **Disposal to the sea and tidal waters**

In view of the large volume of seawater, the influence of a project on the sea or on marine environments cannot be large compared with other disposal sites. Although salts do not pollute the sea, other pollutants can alter coastal ecosystems, especially in estuaries. Discharge of drainage water directly into the sea is desirable from an environmental point of view, but it is usually restricted to coastal areas, unless long main drainage channels are dug, which serve also distant inland drainage catchment areas, e.g. the Left Bank and Right Bank Outflow Drain, Indus Plain, Pakistan, and the Bahr el Baqr Main Drain, Nile Delta, Egypt.

Discharge to the sea or associated waters is achieved:

- directly by gravity through outfall drains with a free outlet;

- through a flap gate or tidal sluice, discharging at low tide;
- through a pumping station.

Because free outlets (sometimes referred to as gravity outlets) may cause flooding of any upstream lands below the highest tides, this option is only possible where the drain base is significantly higher than the high-tide level, taking into account the head losses in the system. Even then, the heavier saltwater may creep considerable distances upstream along the bottom of the outflow channels. In addition to the intrusion of saline water, free outlets have other risks because they depend on the currents in the sea, are liable to be closed again by the moving sands along the coast (littoral drift), and can be eroded severely by wave action and currents along the coast. Protection against these forces is generally very expensive, where practically possible, as coastal jetties may be required and extensive dredging operations may be needed to maintain the free flow through the outlet.

Where water is discharged to the sea at levels that are below the highest high-water level, then there is a need for either pumping facilities or tidal structures in combination with “bossoms” with sufficient capacity to temporarily stock drainage water flows, below acceptable main drain levels whenever seawater levels impede free outflow. This is common in drainage catchment areas in flat coastal zones that may suffer seasonally from heavy rainfall, e.g. in monsoon climates.

Tidal sluices and flap gates can keep out high tides and provide discharge during the ebb tide. They are combined with dykes to keep out high outside-water levels. The tide sluices and gates close automatically at high water levels and they open at low tide. Therefore, the continuing upland drainage water flows need to be stored (e.g. in nearby topographic lows) below a pre-set level in order to avoid flooding cropped land during the period of sluice closure. However, although the flow of water is outward only, a discharging tidal sluice is still only partially able to prevent seawater intrusion by salty undercurrents flowing inland under freshwater in the channel.

Flap gates are placed in a small outlet sluice or in a culvert outlet through a dyke. They are commonly used for low discharges, whereas sluices are used where the discharge is higher. Both are efficient when the tides are strong as they need a certain tidal difference in order to work properly. The risk of restrictions below these structures due to sand movements noted for free outlets also applies to the proper operation of these structures.

Favourable locations are estuaries, where the tidal differences are usually greater than in the open sea, and coastal lakes, which are usually better protected from high sea extremes while offering suitable locations for the construction of “bossoms”. Moreover, the risk that tidal sluices may be obstructed by moving sands along the coast is lower in estuaries. Where the coastal waters are shallow, high inland winds will cause storm surges, which may cause outlet stagnation for several days and sometimes even disastrous floods (the North Sea, the Gulf of Bengal and the Plate River).

The presence of periods where no discharge is possible requires storage possibilities above the sluice. These take the form of a large pond, large channels or a low-lying tract of land where flooding is allowed during critical periods (e.g. a storm surge in combination with a high design discharge).

Pumping stations are usually considered for coastal lands lying below a level where tidal sluices cannot provide proper relief and for inland topographic lows without a proper gravity outlet. They are used in combination with dykes that keep out the flooding waters. They require higher costs of investment and operation, but they do not allow saltwater intrusion into the outflow channel.

### **Disposal to a lake**

In projects where drainage water is discharged to lakes and thus comes into contact with air for a considerable time, water will purify somewhat. Many lakes have an

outlet that discharges into a river or into the sea. In these cases, the water quality consequences of a project may differ considerably from the case where drainage water is discharged to the sea or a river, especially where the lake is shallow or small. In order to protect the water level and the quality regime of the lake from excessive alterations, direct discharge by a waterway around the lake into the river or the sea may be an option.

Lakes without an outlet (tail-end lakes), often found in arid regions, behave in a different way. Here, the influences are far more pronounced. The delicate balance of the lake between inflow and evaporation is disturbed easily, and this has led in some cases to overflow or drying up with rapidly increasing water salinity (e.g. Qarun Lake, Egypt; the Aral Sea, Kazakhstan; and Manchchar Lake, Pakistan). In nearly all cases, the salinity of the lake increases more rapidly, and the larger amount of plant nutrients, silt and pollutants may affect its whole ecosystem unless compartmentalization provides relief. If this is not acceptable, alternative disposal sites, such as evaporation ponds, must be found.

The water level in lakes is rather constant, and special precautions against floods are seldom needed.

### **Disposal to a river**

In many development schemes, disposal of drainage water is back into a natural river system directly or eventually through wetlands. In this case, the drainage water discharged from the project area is part of the water resource supply for downstream water users, and it will form a potential source of pollution of the river downstream of the discharge point.

A drainage outlet into a river alters its outflow regime (especially in small rivers). Salinity may affect downstream interests, and plant nutrients or pollutants may also exert their influence on ecosystems. Attention must be given to changes in river morphology caused by erosion and siltation. Large-scale constructions are sometimes undertaken in order to avoid pollution of a river with drainage outflow from very large projects (e.g. Right Bank and Left Bank Outflow Drain, Indus Plain, Pakistan) or urban and industrial developments (Bahr el Baqr Main Drain, Nile Delta, Egypt).

Most rivers have floods, sometimes seasonal, sometimes of shorter duration, but even so, they may last longer than a few days. If the outlet is open, the floodwaters will back up into the project area, which is usually not acceptable. Where it is protected by a sluice or flap gate, the normal upstream discharge may have the same effect. For simple cases, a computer program may provide some indication about these backwater effects (Chapter 5). One solution is an extended outlet channel with an outlet further downstream. In other cases, a pumping station is preferred. Much depends on the local circumstances, especially on the river gradient and the duration of high water levels blocking the drainage outflow.

### **Evaporation ponds**

Evaporation ponds are sometimes used in arid climates for disposal of saline water in inland drainage projects where no other possibilities exist. Natural depressions are sometimes used, but artificial ponds are frequently constructed. Where possible, a number of cascading ponds are used to maintain a constant water level in order to achieve suitable environments for waterbirds.

In order to design evaporation ponds, the composition of the inflowing drainage water should be known and the inundated area must be calculated on the basis of the water balance needed to control the salt concentration in the pond. In this way, part of the cascading ponds can eventually be used to store water temporarily for reuse during dry periods, unless it needs to be disposed to nearby rivers when their discharges have increased sufficiently.

However, an evaporation pond disposal system has environmental drawbacks:

- It is inevitable that the ponds will become salt lakes, in which other pollutants will also concentrate.
- Toxicity levels can be reached by trace elements discharged to ponds where they are concentrated by evaporation.
- Some pollutants might be highly toxic to wildlife and could bio-accumulate through the aquatic food chain.
- Percolation water of poor quality might contaminate shallow groundwater and, later, deeper aquifers by density currents; then, impermeable pond liners must be used.
- Seepage from ponds might cause waterlogging and soil salinization in the adjacent areas.

In addition to these problems, there is a risk of saline dust storms if the pond falls dry when evaporation exceeds inflow.

In the absence of toxic elements, evaporation ponds may initially become interesting wetlands, although these are not sustainable. Where toxic elements are present, alternative or compensation habitats should be provided for waterfowl in order to minimize the negative impact on wildlife.

Therefore, evaporation ponds are only a disposal option where safe discharge to natural waterbodies is not possible. The technical, economic and environmental feasibility of this option depends on the water quality of the drainage water and on the topographical and geohydrological conditions of the available areas.

Details on the evaporation ponds constructed in the San Joaquin Valley, the United States of America, are described in FAO/ICID (1997).

### **Constructed wetlands and related systems**

The drainage water volumes can be reduced and the water can be purified to some extent by guiding the drain flow through a series of artificial wetlands and related systems as discussed below.

Individual wetlands have different types of vegetation (planted or natural), such as grasses and reeds, and even trees, that will reduce the concentration of minor element constituents and provide sedimentation of soil particles and attached contaminants. The first wetland is planted with salt- and pollution-tolerant plants and the following ones have increasingly tolerant plants. These systems can be valuable for removing excess N, P, potassium (K), organic wastes and many other substances, especially those adsorbed to soil particles and those susceptible to biodegradation (FAO/ICID, 1997). For this purpose, water depth must be adapted to plant requirements and the water flow must be controlled in order to provide plants with enough time to take up pollutants. As the upstream basins evaporate a large part of the water, the low volume of concentrated drainage water remaining can be discharged to evaporation ponds or other safe disposal areas.

Artificial wetlands can sometimes be used to protect irrigated lands from wind-blown sands and desert encroachment, for wildlife, as shelter belts with salt-tolerant trees, etc. Another possibility is their use as fish ponds. However, where the fish is to be consumed, periodic monitoring for bio-accumulation of toxins is needed.

If the wetlands are not watertight and the aquifer is not confined, the underlying groundwater will be polluted by leakage. This may become a problem where the groundwater is valuable for purposes such as municipal water supply or irrigation. Therefore, wetlands require careful design (one that considers the topographic, soil and geohydrological characteristics of the site selected) and attentive management.

Where salinity is the main concern, related concepts that are being tested in a number of locations are saline agriculture/forestry systems and land application systems. In the former, drainage water is used to grow a series of increasingly salt-tolerant crops

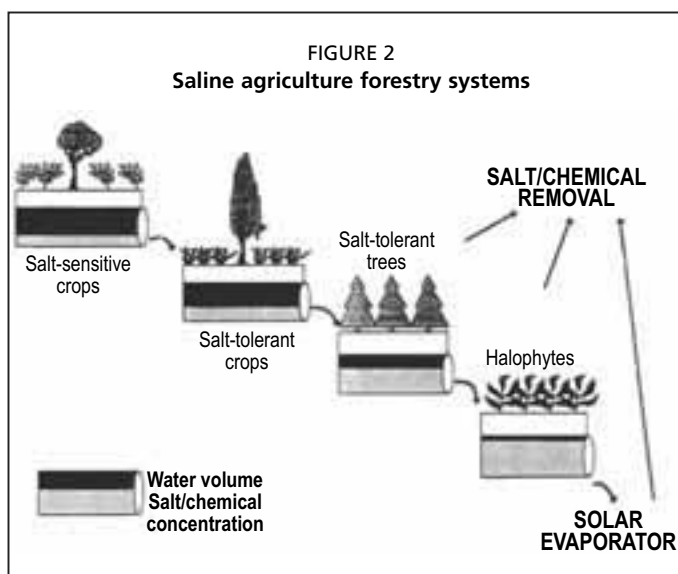


and other plants. With such systems (Figure 2), the drainage water is used progressively, without mixing with freshwater (or with minimal mixing during germination and early seeding stages), as follows:

1. salt-sensitive crops or freshwater wetland where the water is still of reasonable quality;
2. salt-tolerant crops or wetland;
3. salt-tolerant trees or wetland;
4. halophytes, fish ponds, saline wetland, etc.;
5. solar evaporator.

In all these compartments except the last one, sufficient natural or artificial drainage should be available in order to obtain a sustainable solution.

Land application systems for disposal of drainage water are often used to protect irrigated lands from wind damage and to control the advance of desert environments. Drainage water is applied to selected desert or to salt-tolerant tree belts planted for windbreaks. In large projects, internal tree belts can also be irrigated with the drainage water, but care must be taken to minimize impacts on adjacent vegetation that may not be salt tolerant. Where drainage water is used for irrigating even salt-tolerant trees, care must also be taken to ensure that no salt accumulation occurs over time. Drainage water application to desert land surrounding a project can help in protecting it from drifting sand and salt dust.



Source: FAO/ICID, 1997.

### Groundwater recharge wells

Injection of drainage water into a deep confined aquifer through recharge wells is used in some areas to dispose of drainage effluent. The aquifer must be extensive and thick enough, and have a large storage coefficient and transmissivity in order to receive the injected water and it should not be overloaded. In addition, the drainage water must be free of silt and debris. Moreover, its quality should be compatible with the aquifer water in order to prevent the formation of precipitates, which might clog the well or reduce the hydraulic conductivity of the aquifer around the well.

The cost of this option is usually a major issue because transport facilities for the drainage effluent are required where the well is far from the drainage outlet. In addition, there are the costs for the construction, operation and maintenance of the well, and the monitoring costs.

There are other environmental drawbacks, such as pollution of valuable aquifers by waters of inferior quality. Therefore, if this option is considered, great care must be taken to determine the aquifer characteristics (hydraulic properties and water quality) in order to prevent potential negative effects.

Details on deep well injection and systems for continuous monitoring are described by FAO/ICID (1997).

### OPTIONS FOR DRAINAGE WATER TREATMENT

Generally, drainage waters are chemically complex but their characteristics depend mainly on the origin of the drainage flow. Salinity is the main concern where subsurface drainage is the major component of the drainage effluent, especially in irrigated lands. However, in certain cases, trace elements may also be present in drainage waters.

Pollutants, such as pesticides and fertilizers, may be present where surface runoff from crop cultivated lands is relevant. Municipal or industrial wastewater is sometimes discharged into agricultural main drains. In these cases, organic compounds (and even heavy metals where factories are involved) may pollute the drainage water.

Adequate treatment of water to improve the quality of the drainage effluent is often expensive and requires careful O&M. Therefore, it is applied only where other disposal alternatives are not effective. However, processes to treat wastewater and water desalination can be used for drainage water where the treated water can be used in an economically viable way, e.g. as irrigation water.

Water can be purified by physical, chemical or biological methods, which are specifically appropriate for each type of pollutant. A wide variety of systems can be considered but thorough studies are necessary in order to design practical and effective systems. Therefore, before selecting the most adequate process, the specific characteristics of each case must be evaluated. FAO/ICID (1997) provides guidelines for the selection process, considering:

- the chemical composition of the drainage water to be treated and the range of volumes expected;
- the water quality criteria for the drainage effluent in accordance with the uses of the recipient waterbody and the regulatory constraints;
- the capital, operation and maintenance costs;
- the land requirements of each process and land availability.

FAO/ICID (1997) recommend carrying out pilot-scale tests before full-scale implementation, once the most promising treatment has been selected, after considering the advantages and disadvantages of the different processes considered in the evaluation.

### **Removal of organic compounds and nutrients**

Stabilization ponds may be used to remove suspended soil particles, minor elements and organic pollutants where domestic wastewater is reaching outlet drains without proper treatment. Through aerobic processes, organic matter is decomposed by micro-organisms into carbon dioxide and water. Pond systems are normally installed in series and provide a slow natural purification. Careful control is necessary in order to ensure a proper residence time in each pond and to monitor effluents (Khoury, Kalbermattern and Bartone, 1994).

Biological treatment systems usually involve the use of bacteria in engineered reactor systems to effect the removal or change of constituents, such as organic compounds, trace elements and nutrients. Algae and wetland systems can also be used in some instances to replace reactors (FAO/ICID, 1997). Biological treatment is effective in removing organic matter, and also N and P in more sophisticated installations, but it is ineffective in reducing dissolved salts.

### **Water desalination**

As salinity is a common problem in drainage waters, water desalination may be a treatment option to reduce the environmental impacts of disposal in inland drainage projects. There are several technically feasible technologies, such as thermal distillation (whereby water is converted into steam, which condenses into high quality water). Through membrane technologies, salts are separated from water either by means of an electric load application (electrodialysis) or by applying pressure to the saline water to force it to flow through a semi-permeable membrane that prevents most of the salts from passing through (reverse osmosis).

Reverse osmosis may be financially attractive to desalt drainage water for agricultural purposes, but only in special cases, such as in intensive horticulture with high-value crops, and where subsidies on capital costs are provided. However, water desalination

may have certain environmental impacts caused by disposal of brines and residues from desalination, and emission of greenhouse gases.

More information on water desalination is available in an FAO publication (FAO, 2006).

#### **Trace element treatments**

Soluble selenium may be removed by reducing it to the insoluble elemental selenium form through anaerobic biological treatment. Artificial wetland cells have also been used in the United States of America at an experimental level to remove selenium biochemically (FAO, 2002b).

#### **Adsorption of soluble pesticides**

These compounds can be removed via adsorption onto granular activated carbon (FAO/ICID, 1997).

#### **Removal of heavy metals**

For non-degradable (persistent) substances, such as heavy metals, physical-chemical treatment of the drainage effluent is possible, such as precipitation by increasing the pH with lime or caustic soda to minimize solubility (FAO/ICID, 1997). However, the costs are usually prohibitive. Hence, application is restricted to special cases, such as the wastewater outlet of a factory. Sometimes such methods are even economically viable owing to the relatively high concentrations and value of the recovered materials (e.g. mercury, as used in chlorine production).

## Chapter 3

# Socio-economic and institutional aspects

### SCOPE FOR DRAINAGE DEVELOPMENT

Drainage is a widely applied water management instrument in developed countries. However, in most developing countries, agricultural productivity and development have yet to reach the threshold level at which drainage becomes a viable investment. Other factors (e.g. lack of awareness among the farmers and policy-makers, institutional weaknesses, and non-conducive government policies) also account for part of the difference in development between developed and developing countries in the state of drainage (Smedema, 2002).

Government commitment to drainage development in many developing countries tends to be ad hoc and not sustained. Interest in drainage may be strong in a high rainfall year but declines when followed by a series of normal dry years. Public support will increase as levels of agricultural and rural development rise, and more farmers and rural communities start to appreciate the value of drainage and start to use their political strength to mobilize support for their cause. This process may be accelerated (through demonstration and education) by pro-actively raising awareness of the need for and impact of improved drainage (Smedema, 2002).

Owing to the lack of sufficient private-sector capacity, drainage development and management in almost all developing countries relies heavily on government initiative and support. However, for long-term sustainability, especially the assurance of proper maintenance, a strong involvement and commitment of farmers' communities is essential. The drainage development and management model that is generally most appropriate places responsibility for the main drainage system with the government or other public body, and that for the on-farm drainage systems with the farmers, with the role of the government limited mostly to creating the proper enabling conditions (policy/legal frameworks, incentives, research and technical assistance, etc.). However, widely tested successful institutional models for participatory drainage development and public/private partnerships have not yet been established (Smedema, 2002).

### FARMER PARTICIPATION

#### The need for a participatory approach

In the planning and design of drainage systems, with their subsequent O&M routines and related activities (e.g. drainage water quality management), stakeholder participation is paramount to the successful long-term satisfactory O&M of the systems and acceptability by the users. Farmers are the primary stakeholders in most agricultural drainage projects. However, other interests such as environmental, community and road authorities are also important stakeholders, and their views should be considered. Design factors should also strive to carry through with the desires of the stakeholders and be in line with the capabilities of the farmers groups. Regardless of whether the project is a new development or concerns the rehabilitation of, modernization of or addition to an existing system, stakeholder participation is important for ensuring its success.

Drainage development activities have proved to be too expensive and too ineffective where carried out by governments or semi-government institutions with public budgets. Therefore, as farmers are the ultimate beneficiaries of drainage development

and as their strong participation in local system O&M is paramount, it is necessary to involve them in the process as early as possible. Some participatory work should be initiated even before planning begins so that stakeholders are involved actively throughout the project development cycle.

Thus, in the planning stage, a general plan for the organization and financing of the O&M of the systems should be drawn up and the role farmers can play therein should be developed. It is difficult to organize a successful users association to operate and maintain a system if they have not had a sincere chance to shape the extent, type, scope and parameters of the facilities installed, or if they have not been involved in decisions regarding the financing of their recurrent and capital costs.

This approach means that farmers should be involved first in the identification of the need for new drainage developments or the rehabilitation and modernization of existing systems. Later, they can participate in the process of planning and design to fully operate and maintain the drainage systems, jointly with the irrigation systems in irrigated lands. They also should be presented with options and provided with discussions on the effect of each option on: production; diversification potential; environmental conditions; and social, economic and health issues. These activities are often undertaken in conjunction with other improvements and they normally require inputs from other professionals in order to be effective.

Through this process, farmers are informed about the options they have and are further involved in making the final decision. If any changes from the initial plan are required, farmers need to be kept informed.

### **Considerations for participatory planning and design**

The system layout should consider the potential users groups and subgroups. A number of factors make it difficult for groups to work together, and sound thinking must go into the system layout in order to avoid among others:

- social conflict stemming from ethnic differences and other factors;
- physical development that would reduce the opportunity for communication between users dependent on one another;
- major differences in cropping systems;
- conflict potential related to infrastructure operation owing to different objectives.

Consideration of other related infrastructure, such as irrigation, flood mitigation works, and road systems, should also be part of the planning and design considerations. Successful operation of a drainage system requires facilities to be compatible, and participatory efforts should discuss the compatibility, strengths and weaknesses. It is not fair to expect users groups to operate and maintain a drainage system that creates problems for operation of irrigation, flood control and other interdependent facilities.

Designers must adopt a system to test the potential interaction scenarios for a variety of climate events. This is needed to assure users groups that operational conflicts will be minimal and to inform them of potential problems to watch for during unusual events. This type of information should all become a part of the O&M plans that should be worked out with users groups for the portion of the facilities that each group or subgroup is responsible for.

Participatory design procedures should be used in order to facilitate cost-effective O&M routines. Consultation with users and all stakeholders during the design process is critical to the future satisfaction of all organizations with the way the system is operated and maintained. Consultation means informing these groups and individuals as to what options they have and how the decision in selecting a particular option would affect their O&M cost, effectiveness, timing and complexity.

### **Drainage system modifications to facilitate participatory management**

Monitoring and evaluation systems are critical to the successful management of drainage systems. Design of the M&E system is best done in conjunction with the designs for infrastructure modification or addition. All facets of the system that could affect sustainable production, the environment and social satisfaction should be considered. Monitoring plans should be developed during the design stage with the users groups that will operate the system, the supervising governmental organization, user group and/or other organizations that have stakes in the M&E of system performance. A system for prompt feedback to system operators and maintenance staff should be included. Timely modifications, adjustments and maintenance are critical for successful project operations.

Structure and facility modifications are sometimes necessary in order to enable improved participatory management. Controls and regulation equipment should be designed with the consent and ability of the users organization in mind. Similarly, measurement devices and monitoring equipment should consider the users organizations' information needs and operation abilities. The individuals operating the facilities should understand any automation facilities fully. Training to ensure that controls, devices and equipment are operated and maintained properly is just as important as having the facilities.

The establishing of beneficiaries' participated organizations in due time in conjunction with the transfer of O&M responsibilities for local existing irrigation and drainage systems is also important. Users organizations can be established at any time, but the earlier the better and preferably in combination with the planning, design and implementation of the water management system rehabilitation/improvement works. However, such organizations cannot take over existing systems effectively without user training and guidance during a start-up period. The financial obligations can be significant and these details must be worked out with potential users organizations prior to transferring the drainage facilities (and the responsibility for their O&M) to them. The training required to perform the functions being turned over to a users group is also critical. The individuals responsible for each aspect of operation or maintenance work must also know who they can call on as resource people if questions come up that they are not equipped to handle or if they need advice. The institutional capacity must be considered when work is being turned over to any organization for operation, maintenance, management and/or monitoring (FAO/ICID, 1997).

## **SOCIO-ECONOMIC INVESTIGATIONS**

### **Procedures**

Drainage design cannot be undertaken in a social vacuum. Consideration in the planning process must involve socio-economic impacts and costs associated with the design. Evaluations of impacts should be made when evaluating alternative designs and when considering changes in the design that are not in line with the original planning concepts. This is necessary as adjustments may have a significant impact on the economic evaluations that were conducted in order to justify the project at the planning stage. It can also have an effect on the social assessments made and on the predicted social impacts.

Agreements must be reached between the involved government organization or specific executing authority and its financiers, designers and the organized beneficiaries on the socio-economic procedures and considerations to be followed. These agreements should be reached early in the planning stage of project preparation, and the design organization must follow these agreements. Formalized contracts with sanctions for both sides of issues that relate to some of the most critical items may be considered as a part of these agreements.

Alternatives should be a part of the planning process. Similarly, alternative designs to accomplish established plans should be considered when preparing designs. It is important to follow established economic and social evaluation procedures. Guidance in economic evaluations has been provided by the Economic Development Institute of the World Bank (World Bank, 1991), the United States Bureau of Reclamation (USBR, 1984), the FAO Investment Centre (FAO, 1995), and the World Bank (Ochs and Bishay, 1992).

### **Costs and benefits**

In most projects, a benefit/cost analysis culminating in a feasibility report is completed in the planning stage. Wherever possible, cost and benefits are quantified, with exception of certain socio-economic and environmental impacts (which are described qualitatively). In the design stage, cross-checks are made as adjustments are contemplated. Early in the planning and decision process, irreversible decisions are sometimes made that influence the cost and impacts of a project and may limit technical choices and alternatives in later stages of planning.

The costs associated with the implementation of drainage works are important and should reflect accurately investment costs and recurrent costs of O&M in relation to the quality or durability of the initial installation. Measures installed by cutting corners will inevitably increase the recurrent O&M costs of the facilities. Therefore, it is important to consider this balance during the planning and design stages of project development. It is also desirable to consider using cost optimization procedures or cost analysis for various aspects of the drainage work.

Costs are dynamic and change with time because of inflation and standard market factors. However, it is also necessary to consider changes in technology. Items such as trenchless drainpipe installation equipment, continuous rolls of plastic piping materials and geotextile envelope materials to protect drainpipe are examples of technology that, when used, have considerable potential for changing the construction costs of drainage systems.

The economic and financial benefits of agricultural drainage projects ("with project" case) relate primarily to increases in agricultural production, crop diversification opportunities and improved food security. These benefits need to be compared with the economic and financial benefits of the "without project" case, which in drainage projects to control waterlogging and soil salinity in arid and semi-arid regions often implies a significant decrease in yields. This decrease can be estimated with crop salt-tolerance data (FAO, 2002b). Thus, in these cases, an important enhancement of the incremental benefits is expected. Secondary benefits relate to items such as lower production costs, but may also include qualitative improvements, e.g. lower incidence of water-borne diseases and improved access to villages.

Quantifiable benefits as a whole should be based on current economic and financial farm prices for products sold or used locally as applied to the estimated production costs. The changes in costs of production, including for example O&M costs, can be deducted from the gross benefit in order to determine the net incremental benefit. The tests that may be used are the ratios of gross farm benefits to investment, and the net farm benefit to investment (Ochs and Bishay, 1992).

Economic efficiency is generally evaluated for a project by traditional economic measures such as the rate of return and the net present value. A conventional assessment should be made of the economic benefits of the directly productive elements of the project. The most common assessment method is to measure the project's internal economic rate of return. This may be defined as the discount rate for which the total present value of costs incurred during the life of the project is equal to the total present value of benefits accruing during the life of the project. In an investment project, costs

are typically bunched at the beginning of the project, whereas benefits begin to accrue only after a lapse of time.

The application of a discount factor enables these costs and benefits to be compared on the basis of their present value. In order to calculate the internal economic return, it is necessary to construct a table showing the cost and benefit streams and the incremental income as they accrue each year during the life of the project. The cost streams used for economic analysis should include the capital costs of the project (including physical contingencies) as well as the incremental operating costs to farmers and any project authority or association. In an early phase of planning, maintenance costs are often estimated and based on a percentage of the capital costs, but care must be taken to ensure realism in these estimates. However, in subsequent stages, maintenance costs must be estimated in detail.

Where the technical life of a component in the project, such as a pumping plant, is less than the economic life of the project, provisions should be made for the cost of replacement (Ochs and Bishay, 1992). Where the internal rate of return is calculated, the replacement of different items at different times depending on the lifetime is included automatically.

Accurate data are necessary in order to provide proper evaluations. Sensitivity analyses should be included in the economic studies in order to be certain that the risks are understood when evaluations are presented to implementation or financing authorities as well as to the beneficiaries and stakeholders.

### **Life expectancy of drainage systems**

The economic life of a land drainage system is an important factor in the economic evaluation for a project. Large drainage schemes, such as those built by the United States Bureau of Reclamation (USBR), predominately for salinity control, are based on a 100-year life expectancy, which could be called the technical life (USBR, 1984). Drainage systems in tropical and humid areas are sometimes built with a life expectancy as low as 25–30 years where they are primarily surface drainage systems. The anticipated actual technical life of a well-maintained pipe drainage system is usually 50–100 years.

However, the economic life of a project is more a consideration of the time at which a project will be renewed. The value of a project is greatest soon after construction and reduces steadily with time until the end of the economic life. The terminal value is generally considered zero. A project could have an economic life that coincides with its actual or expected design life, but future costs that occur after about 30 years are insignificant in economic terms. Thus, the economic life is generally taken to be 20–30 years (Smedema, Vlotman and Rycroft, 2004).

### **Cost recovery**

Cost recovery considerations regarding investments in new drainage systems should not always be thought of in the same manner as for irrigation system installation. Major drainage facilities for a project area are normally considered a public good. This is because they benefit entire communities or regions and normally provide secondary jobs, resulting in poverty reduction in areas much larger than the actual project areas. Thus, they should receive more government financing. Therefore, the investment costs of public drainage facilities that protect numerous landholdings and provide a public good owing to control of salinization, waterlogging and flooding are not often required to have extensive cost recovery from the direct beneficiaries (Smedema and Ochs, 1998). The main drains are considered to be more of a regional benefit similar to public works such as roads, bridges, utilities and other infrastructure that provide incidental protection and secondary benefits. However, recurrent O&M costs of the public drainage system should be recovered as much as possible and in accordance with the level of benefit that accrues to individual project stakeholders.



Drainage facilities on private land and facilities for small groups of farmers are usually considered as private investments. The costs for constructing, operating and maintaining these smaller facilities should be recovered from the direct beneficiaries.

In areas with mature drainage systems that need to be repaired or rehabilitated, organizations of drainage boards or drainage districts become common. Drainage improvements in these areas are normally carried out using the normal cost-recovery procedures used for local irrigation project areas (Smedema and Ochs, 1998). Thus, the beneficiaries pay for improvements to their own systems and even the larger civil works that involve numerous landholdings and provide some incidental public good. In irrigated areas, where the irrigation district is normally the user organization responsible for drainage facilities, cost recovery is carried out for the drainage work and assessments are made for the beneficiaries that benefit directly from the work.

### **Operation and maintenance costs**

O&M costs are recurrent and must be planned for prior to initiating any construction or improvement work. Planning and design should not be restricted to defining the technology of the systems. Consideration is also needed on how these systems are to be operated and maintained. System designs and institutional design of its O&M arrangements should be fully compatible.

An organization with the authority to perform the O&M that is required at the time it is required, with the financial capacity to carry the involved costs, and with the skills necessary to recognize the needs, should be in place when the construction is completed or segments of the work are transferred to it. The earlier this organization is established the better as it should be thoroughly familiar with the construction complications and the impact they may have on O&M.

Cash flow and accounting systems are critical to the successful performance of the local/regional organization responsible for O&M. Training of appropriate individuals is critical to carrying out this responsibility effectively. The cash flow and accounting systems must be transparent and understandable to all interested parties. Numerous appropriate cash flow and accounting systems are available, also in the rural communities throughout the world, and should be used.

Auditing of the financial and physical systems is also an important factor. The organization responsible must be certain this is done in an unbiased way. Financial audit refers to independent audit of the accounting work done and it should be undertaken at least annually. Physical M&E is also necessary to reflect the needs for special maintenance efforts, improvement work and operational changes. Conscientious monitoring and serious prompt evaluation of the monitoring data will help ensure system sustainability and operational success of the system in an efficient manner.

### **Social evaluations**

The social impacts of drainage projects on the population can be both negative and positive. It is important to assess and evaluate, at least in qualitative terms, the probable social changes that will result from each alternative design. This is usually done on a project-wide basis and may include consideration of related infrastructure work, such as irrigation or flood control, that is being implemented at the same time.

Base studies may be needed to establish the existing social situation in an area. Social impact evaluations should include details necessary to establish potential benefits and losses. Sometimes these evaluations are done in conjunction with EIAs. *The ICID environmental check-list* (ICID, 1993) and *Environmental impact assessment for irrigation and drainage projects* (FAO/ODA, 1995) provide a good starting point.

Social scientists should be used to undertake these impact evaluations. They have valuable tools, such as matrix systems, that can help to ensure the accuracy and

completeness of the evaluation. Social implications relate to the number of beneficiaries and losers from the drainage activities.

Important factors to consider include:

- impacts on living standards (lifestyle changes and cultural heritage);
- changes in the cost or value of land experienced by farmers;
- nutritional results anticipated;
- educational resultants;
- changes in the role of women;
- food security;
- poverty alleviation;
- health and disease issues (vectors, schistosomiasis, and water-borne);
- relocation or resettlement impacts (human migration potentials);
- services such as health and social services;
- equity issues (resulting social gains and losses caused by new facilities).

## Chapter 4

# Drainage studies and investigations

### INTRODUCTION

Drainage studies and investigations may be carried out for different purposes and at different scales. The type of information required and its level of detail depend on the specific objectives of the phase of the project, the size of the area and the complexity of the problem. Other factors, such as the time and funds available to finance the study, are also considered. Two major groups may be considered: (i) master plans, at national, regional or river basin level; and (ii) drainage studies in a specific project area.

Drainage master plans are necessary in order to: (i) identify large areas with waterlogging and salinity problems; (ii) formulate priorities from a policy, technical, environmental and socio-economic point of view for developing specific drainage projects; and (iii) strengthen involved water management institutions and executive farmers organizations where required. The drainage plan is frequently a component of a regional development plan. Then, integration of the different components of the land and water project is essential. Sometimes, for large areas, such a regional master plan precedes more detailed studies, such as those listed below.

In a prioritized area, which should preferably be a hydrological catchment, studies and investigations are required for the planning and design of an appropriate drainage system. For large-scale drainage projects, three study levels are usually needed: (i) identification; (ii) feasibility; and (iii) detailed design.

The identification study includes a reconnaissance of the whole area in order to: (i) globally identify waterlogged or salt-affected lands; (ii) assess the natural drainage capacity of these problem areas; (iii) consider possible causes of the drainage problems and outline technical solutions; and (iv) give a first estimate of the benefits and costs, and of the socio-economic and environmental effects of the project.

The feasibility study refers to a properly identified potential drainage project area and elaborates on the selection of the most appropriate solution for the drainage problem in technical, environmental, socio-economic and financial terms.

The design study includes detailed investigations for areas with positive feasibility results, and aims at the final design of the drainage system and associated engineering works. This study consists mainly of soil investigations to determine the spatial variation of soil hydraulic characteristics and hydrological observations to characterize carefully the surface and groundwater flows.

In small-scale drainage projects, the feasibility and design phases can be combined into a single study.

Investigation and study costs should be minimized, especially where doubts exist whether the intended drainage project will be feasible, but also during the design study phase. In addition to financial reasons, organizational and topography reasons mean that it is not possible to provide each and every patch of land with the theoretically best drainage provisions. Therefore, depending on the level of sophistication of equipment, available materials, and contractors' experience and organization during the project implementation phase, the minimal size of subsurface drainage units with one specific drain depth and drain spacing may reach 200 ha in some developing countries. For similar reasons, public main drains cannot always follow an ideal alignment.

Consequently, field information should not be collected to reach an accuracy that exceeds the requirements of the implementation practices.

In addition to the above studies focused on new drainage projects, investigations are frequently made in already drained lands. Generally, these observations are made in order to: (i) check or establish drainage criteria; (ii) assess the performance of existing drainage systems; and (iii) identify poorly functioning features that may jeopardize the correct technical operation of the drainage system. Investigations are also needed to identify negative environmental impacts of the system (to formulate correction measures later), and to assess the socio-economic return of drainage investments. Observations are also made to modernize drainage systems, for example, by designing structures for controlled drainage. Moreover, investigations in drained lands can also provide useful information for drainage design as they permit checking of the soil hydraulic characteristics and criteria used.

FAO has already addressed the issue of investigations in drained lands (FAO, 1976). As FAO is planning a new Irrigation and Drainage Paper on evaluation of the performance of land drainage systems, this chapter describes only those investigations in drained lands useful to deriving drainage design factors and soil hydraulic characteristics for designing new drainage systems.

Drainage studies at their different scales generally require information commensurate with different grades of detail according to the level of the study. This information can be obtained from:

- aerial photographs and satellite images;
- topographic maps;
- land-use maps;
- climate data;
- soil investigations;
- hydrological studies;
- crop, land and water management data;
- EIAs;
- socio-economic evaluations;
- institutional considerations related to the implementation and subsequent recurrent O&M requirements of the drainage project.

Table 3 summarizes the characteristics of drainage studies and the specific information needed for each level of detail. Table 3 shows that the intensity of the study and the map scale increase from master plan to design, but that the area studied decreases accordingly. Depending on the level of readily available information, the costs of these studies average less than 3 percent of the costs of implementing the system where no expensive specific geohydrological studies are required. The benefits of a sound planning and design process are considerably greater.

The following sections describe the sequence of studies. Reference is made to the drainage investigation guidelines compiled in the FAO Irrigation and Drainage Paper *Drainage design factors* (FAO, 1980), which are still largely valid. Additional information on this subject is available in studies by the Van Aart and Van Alphen (1994), the USBR (1984), Madramootoo (1999), and Smedema, Vlotman and Rycroft (2004).

### **DRAINAGE MASTER PLANS AT NATIONAL OR RIVER BASIN LEVEL**

National and regional drainage master plans are normally combined with other aspects of national and regional development, such as irrigation, flood mitigation, and land-use planning. However, they are sometimes specific in order to solve a severe problem, e.g. soil salinity.

After a brief description of the country or region (general information), especially focused on the economic aspects of rainfed and irrigated agriculture, the first phase

TABLE 3  
Components of drainage studies

Type of study	Objectives of the drainage study	Maps (based on available topographical background)		Climate	Soils & land use	Hydrology	Crop, land & water management	Environment	Socio-economic analysis
		Content	Scale						
Master plans	Identification of drainage needs at national or river basin level; formulation of priorities	Agro-ecological areas	1:200 000 1:100 000	Type of climate; average data on precipitation & evapotranspiration	Available information on soil associations & land use	Available information on general surface water & groundwater flow	Available general information on agricultural systems & on irrigation & drainage development	Available information on environmental problems related to water management	Available information on drainage costs, returns & cost recovery; institutional development concerning land drainage
Identification	Identification of problem areas; assessment of drainage needs; pre-feasibility considerations	Land classification; mapping drainage subclasses	1:50 000 1:25 000	Climate characteristics; average precipitation & evapotranspiration	Soil reconnaissance study & land use; based on satellite image or aerial photographs interpretation	Reconnaissance of surface & groundwater hydrology; irrigation practices	Estimation of drainage coefficients & crop water management requirements	Assessment of environmental problems related to drainage & need of EIA	Estimation of benefits & costs of drainage developments in problem areas; information on water users organizations & involved government organizations
Feasibility study	Outline of main drainage systems; formulation of typology of field drainage systems; technical, socio-economic & environmental feasibility aspects	Soil & groundwater maps; layout of the main drainage system	1:10 000 1:5 000	Analysis of extreme rainfall & extreme droughts	Determination of soil hydrological & soil salinity characteristics; based on interpretation of time series of satellite images or aerial photographs	Characterization of groundwater flow; analysis of extreme discharges; availability & quality of irrigation water	First estimate of specific design discharges for channels & drains; critical time of ponding, waterlogging & soil salinity level in relation with crops	EIA of the drainage development	Calculation of the benefit/cost ratio & the internal rate of return; description of social impacts & gender issues
Design	Drainage systems design	Drainage systems layout	1:5 000 1:2 000	Analysis of extreme rainfall (results of the planning phase)	Average values of transmissivity of major soil units	Detailed groundwater flow (based on results of the planning phase)	Drainage design coefficients; required drain & groundwater depth	Detailed EIA of the drainage works & formulation of the mitigation plan	Budget of the designed drainage systems & auxiliary structures; assessment of O&M costs in relation with type of responsible organization
Investigations in drained lands	Check design drainage criteria & soil hydraulic characteristics	Layout of the observed drainage system	1:2 000 1:1 000	Current rainfall data	Soil hydraulic characteristics; soil salinity	Groundwater observations; drainage flows	Actual irrigation practice	Drainage water quality M&E	Ex-post determination of crop yields, crop schedule shifts & financial returns

of a national or regional master plan is to define large-scale agro-ecological areas. These areas are distinguished on a physiographic basis, considering climate, soils, hydrological conditions, and land-use and agricultural systems. In each area, current drainage development and drainage needs must be identified, considering separately: excess rainfall, irrigation losses, water shortages and soil salinity control. Finally, priorities concerning the various areas are indicated.

Generally, existing data form the basis of master plans. Therefore, they are formulated using the available information on: climate, soils, hydrology, land use, irrigation and drainage development, environmental problems and socio-economic aspects related to water management, and institutional development concerning agricultural drainage, with some additional information if needed. Checking on consistency and consolidation of the information is important and one of the main purposes of such plans.

Where funds are available for regional studies or at river basin level, a general reconnaissance is sometimes made in order to provide basic information on existing land use and to identify problem agro-ecological units. Remote-sensing techniques, with limited field observation support, are usually applied to locate the major soil associations and land systems of the area. Most field observations are visual. Information from geological maps is also valuable. The density of these observations is very low, about one site per 1 000–5 000 ha, according to the size of the area. Thus, the scale of the final maps may vary from 1:100 000 to 1:200 000. This basic information may be compiled into a geographical information system (GIS) by means of thematic maps that can be updated periodically. Details on the use of GIS for the planning and design of drainage systems are available in Chieng (1999).

The physical information is complemented with information on public-sector development as concerns drainage in education, research, training, project development and budgets. In this way, by comparing the drainage needs in each large-scale agro-ecological unit with the current drainage development, the master plan can be formulated and priorities defined. The master plan must include recommendations for planning, design and construction of new drainage systems and for capacity development, considering drainage as a component of integrated water resources management (IWRM). This plan may serve as a basis for the more detailed studies to follow.

### **IDENTIFICATION OF PROBLEM AREAS**

In a specific zone, the first phase of a new drainage project is to identify the problem areas and to characterize the soil salinity and/or waterlogging problems, i.e. excess surface water, overirrigation and existence of perched water tables or shallow groundwater tables. In addition to this, the general characteristics of the existing drainage facilities must be described. Where possible, historical information and views of stakeholders and future beneficiaries should be sought and taken into consideration. In this way, the new surface and subsurface drainage needs and their related costs can be estimated. The drainage solutions identified for the affected areas are later developed in detail in the next planning phase.

### **Climate information**

In the identification phase, the main features of the required climate data are the atmospheric components of the water balance: precipitation, evaporation and, in some areas, snowmelt. Temperature correlates roughly with potential evaporation, but there are better estimation methods for this quantity where long-term measurements are not available or are of doubtful quality. Once the potential evaporation is known, crop evapotranspiration, which is an essential component of the water balance, can be determined. Effective rainfall is also essential to formulating the salt balance.

For identification purposes, available average values of the above-mentioned climate parameters, their seasonal distribution and their spatial variability are sufficient.

Methods to determine evaporation, crop evapotranspiration, and evaporation of fallow land have been described by FAO (1977a and 1998). FAO (1974) has also provided guidelines to determine effective rainfall and the annual, seasonal and monthly water balances.

### **Landforms, soils and land use**

Land-use and natural vegetation information, inferred from satellite images, aerial photographs and field visits, can give important clues for identifying waterlogged and salinized areas as some visible crop reactions (e.g. poor growth, patchy pattern, rolled leaves and pale colour) are indicative of soil salinity. Land-use information is also necessary to estimate the benefits obtainable if the drainage problems of the project area are solved. For identification purposes, available land-use data are generally used. Some countries have this kind of information on maps at scale 1:50 000. The main constraint is updating/validating this information. For this purpose, farmer participation is indispensable. Remote sensing (RS) supported by fieldwork is a useful tool to produce new maps or to update existing ones.

However, in order to differentiate those areas affected by waterlogging and salinity from salt-free lands with adequate natural drainage, soil mapping focused on assessing land drainability is frequently required. Existing soil maps, where available, are seldom appropriate for drainage purposes. This is mainly because conventional soil classifications are generally based on soil information restricted to some 150 cm, but layers below this standard depth are commonly relevant for drainage purposes. Therefore, observation depths should exceed those for conventional soil surveys and be at least 2–3 m. In addition, knowledge of the substrate down to the impervious layer is required. This can be derived from deep observations or from geological maps.

The physiographic approach for mapping soils (Veenenbos, 1972) is particularly suitable to identifying problem areas. This is because a close relationship exists between drainage conditions, soil salinity and geomorphology. The “Russian School” has stressed the relationship between geology, geomorphology, waterlogging and salinity (FAO/UNESCO, 1973). This approach has also been described by Bardají (1998) and applied successfully in Spain. Following this approach, once the landforms of the studied area have been mapped through a photo-interpretation study, field observations are made in order to find the causes of the observed phenomena. Generally, waterlogging and salinity occur in the lowest places and in locations where upward seepage occurs.

Aerial photographs (with scales from 1:20 000 to 1:40 000) and satellite data are of great help because the waterlogged and saline areas are often much better identified than on topographic maps. Moreover, photographs are usually more recent than existing maps, and satellite data are even more up-to-date, while time series of satellite images may reveal trends in problem development.

In this phase, reconnaissance studies at scales from 1:50 000 to 1:25 000, depending on the size of the project area, are sufficient. The observation densities depend on the intensity of the survey, but they can vary from one to four observations per 100 ha, localized mainly in the problem areas.

The main purpose of these observations is to determine: (i) the relative position of the mapping unit in the landscape; (ii) the salinity conditions; and (iii) those soil characteristics required to assess land drainability, such as the infiltration rate, the internal drainage and the transmissivity of the subsoil down to the impervious layer. These soil characteristics, in particular the hydraulic conductivity, are often estimated in this phase from two basic soil physical properties: soil texture and structure (Annex 1). Other features that can be observed in the soil surface, such as wet spots, white spots and puffs, and in the soil profile, such as mottling and the distribution of soil moisture, are useful to understanding land drainability. Average data of these soil characteristics should be obtained for each mapping unit.

### Hydrology and irrigation practices

In the identification phase, the general pattern of the surface and groundwater flow should be determined. This can be obtained from the available hydrological information of the project area. It is sometimes necessary to prepare an inventory of data from the existing observation points, such as groundwater wells and permanent gauging stations of the watercourses network. Other field observations on natural vegetation and in particular on channels (presence of small mud volcanoes and failing side slopes) can indicate areas affected by seepage. About one observation per 100–200 ha is sufficient at this stage.

A description is usually required of the public irrigation water supply management and the field irrigation practices (where drainage water excesses are also thought to stem from overirrigation). In this respect, field visits to tail ends of the lower irrigation command areas may be revealing.

Information on the quality of the irrigation water and on salinity of the groundwater is also desirable at this phase.

With the hydrological, soil and irrigation-practice information, the areas affected by waterlogging and salinity can be mapped and the general characteristics of surface water and groundwater flow can be understood. For example, Figure 3 shows the soil map of an irrigation district in northeast Spain. This map identifies clearly the areas with excess water.

This map shows: the lowest part of an alluvial plain with fluvial terraces (T), the actual floodplain with levees (B), backswamps (D) with intermediate transitions (t), and an estuarine plain (LL). Additional landforms (R) have not been subdivided in this map because they are well drained. The main characteristics of the above mapping units are described in the map legend. The areas affected by waterlogging and salinity are restricted to the backswamps and transitions of the floodplain and the estuarine plain. Therefore, the planning of new drainage systems will focus only on these areas.

### Soil salinity

As soil salinity is a major problem in the irrigated areas of the arid and semi-arid regions, mapping of soil salinity is usually an essential component of identification studies. Areas where soils with severe salinity predominate should be set aside and perhaps not be included in the reclamation project in order to minimize the mobilization of salts and reduce the negative impact on drainage water quality.

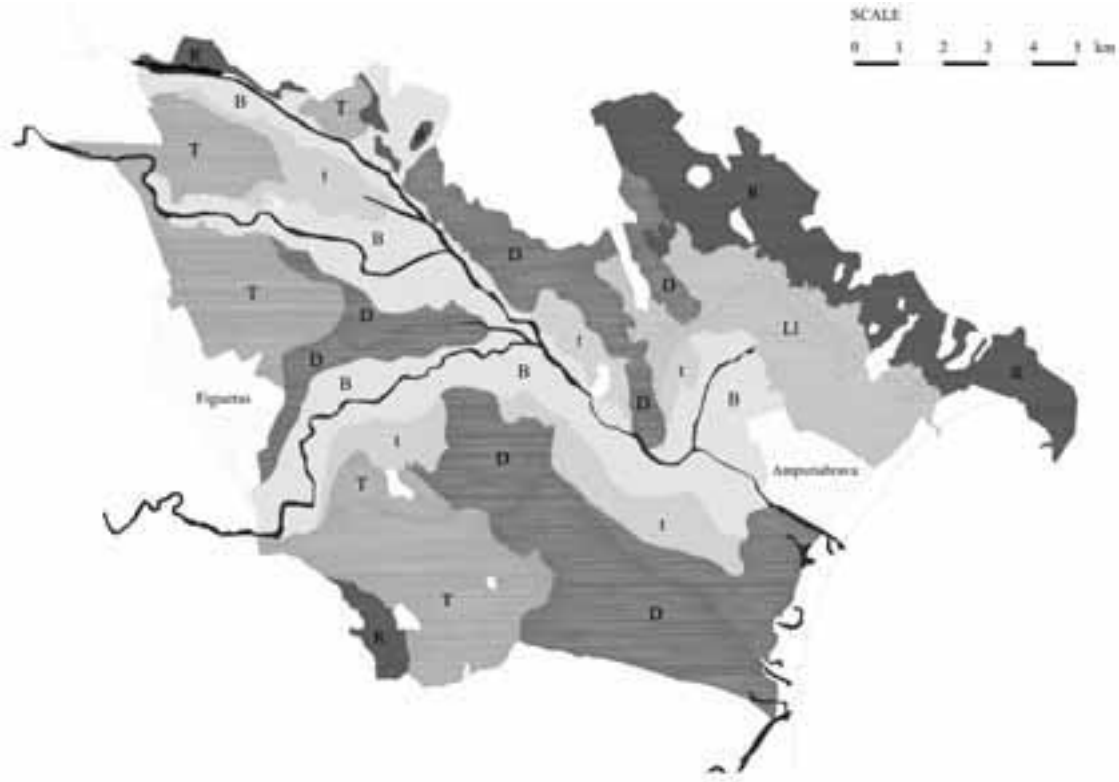
Soil salinity has usually been determined by laboratory analysis from soil samples. Generally, the electric conductivity ( $EC_e$ ), anions, cations and pH are determined in the extract of the saturated paste. This extract is the reference soil water extract for measuring soil salinity, and the salt tolerance of crops is always expressed in terms of  $EC_e$ .

As determining the  $EC_e$  requires laboratory equipment for the preparation of saturated extracts, quick yet reliable field estimations of soil salinity can also be derived from EC measurements in 1:2 soil solutions ( $EC_{1:2}$ ) or more frequently in 1:5 ( $EC_{1:5}$ ). A 1:5 soil solution can be obtained after filtering the liquid resulting after mixing 100 g of dry soil with 500 g ( $\approx$  500 ml) of water. The relationships between the field data expressed as  $EC_{1:2}$  or  $EC_{1:5}$  and the reference values expressed as  $EC_e$  are very site specific because they depend on soil texture and the presence of slightly soluble salts. Therefore, for accurate determinations, the recommendation is to obtain local correlations.

Where the salinity problem is extensive, costs can be reduced by direct field measurements of the EC. This can be done by means of a four-electrode probe, which can be used for measurements of the EC at depth intervals of about 25 cm down to a depth of 1 m. To obtain reference  $EC_e$  values from field measurements, calibration of the equipment is required. The EC probe can be useful for monitoring measurements made with similar moisture content as the EC value determined with the probe depends on, in addition to the soil salinity, the soil moisture content.



FIGURE 3  
Simplified soil map of an irrigation district identifying areas affected by waterlogging and salinity



Symbol	Landform	Soil phase	Soil properties				Topo- graphy	Drainage				
			Effective depth (m)	Surface texture (m)	Subsoil	Salinity		Slope (%)	Soil drainage	Ground water level (m)	Impervious layer (m)	Hydraulic conductivity (m/d)
B	Floodplain levees	Well-drained alluvial soils	> 0.9	Loam, sand-loam	Sand	Free	< 2	Moderately high	1.5-2.0	> 3.0	2-3	Sufficient
D	Floodplain backswamps	Poorly drained alluvial soils	> 0.9	Loam, clay-loam	Clay	Moderate	< 2	Moderate	0.5-1.0	1.0-2.0	1-2	Insufficient
t	Floodplain transitions	Moderate poorly drained alluvial soils	> 0.9	Loam, sand-loam	Clay	Slight	< 2	Moderate	1.0-1.5	2.0-3.0	2-3	Insufficient
T	Fluvial terraces	Well-drained alluvial soils	0.6 - 0.9	Sand-loam, loam-sand	Gravel	Free	< 2	Moderately high	> 2.0	> 2.5	-	Sufficient
LI	Estuarine plain	Poorly drained alluvial soils	> 0.9	Silt, silt-clay-loam	Clay	High	< 2	Slow	< 1.0	2.0 - 2.5	3-5	Insufficient
R	Miscellaneous landforms with natural drainage	Well-drained colluvial and residual soils	Variable	Variable	Variable	Free	> 2 Variable	Moderately high	> 3.0	Variable	Medium high	Sufficient

Sources: Adapted from IRYDA, 1989a, and Martínez Beltrán, 1993.

Quick measurements of the soil salinity without the need to bore holes can be done with an electromagnetic sensor, which is easily managed on the soil ground. To determine the EC values at different soil depths, the sensor is situated at different

heights above the ground, in the horizontal position for measurements to 1 m depth and in the vertical position for 2 m. Calibration is also required to relate the field values to the  $EC_e$ .

Additional details about direct field EC meters have been described by FAO (1999). As these sophisticated methods are expensive, their use is restricted to soil salinity measurements at the field level in large-scale projects.

RS is being used for soil salinity mapping in several countries with different approaches. For example, the Mexican Institute for Water Technology (IMTA) has applied RS techniques in several irrigation districts in northwest Mexico (Pulido Madrigal *et al.*, 1999, 2000 and 2003b) by applying methods developed by Wiegand (2000). Soil salinity was determined indirectly through indicator crops, such as wheat, cotton and maize. The first step was to correlate global soil salinity ( $EC_g$ ) with crop yields by field measurements and later crop yields with the spectrum values of the following bands of Landsat images:  $TM_2$  (green, from 0.51 to 0.56  $\mu\text{m}$ ),  $TM_3$  (red, from 0.62 to 0.76  $\mu\text{m}$ ) and  $TM_4$  (infrared, from 0.7 to 1.5  $\mu\text{m}$ ). For example, the regression equation obtained in the Rio Fuerte Irrigation District through the spring–summer maize was:  $EC_g = 5.1863 - 0.1896TM_2 + 0.2835TM_3 - 0.0724TM_4$  with a correlation coefficient of 0.85. A lower coefficient of 0.67 was obtained for cotton, which is more salt tolerant than maize and covers the ground less. Probably, better correlation would have been obtained if RS had been applied jointly with the physiographic approach described above and the regression analysis had been made independently for each type of soil. In these districts in Mexico, crop growth under full irrigation is affected mainly by soil salinity. This because other limiting factors, such as water management and agricultural practices, are less relevant when water is fully available. Detailed information on this methodology is available in Pulido Madrigal *et al.* (2003a).

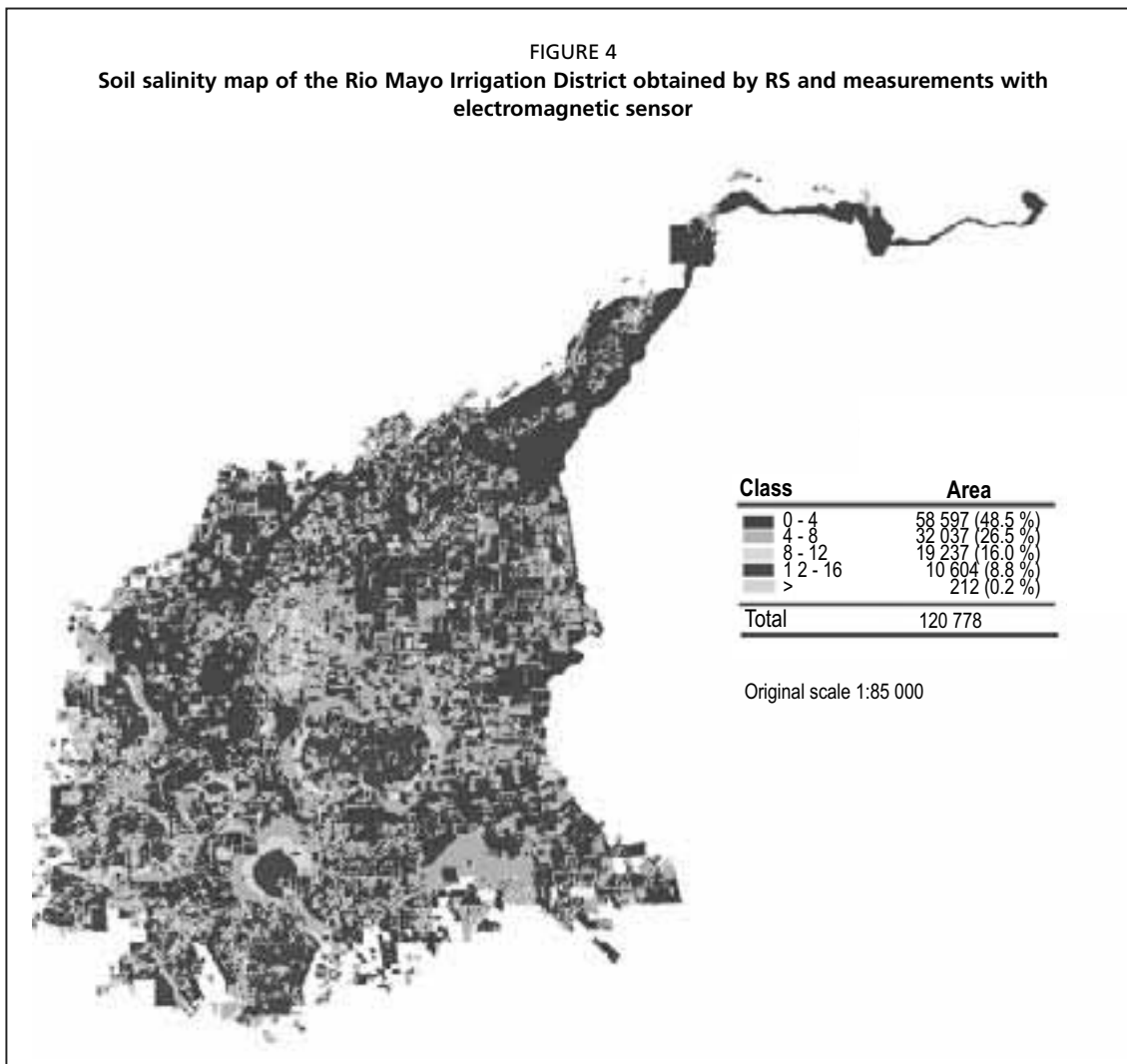
Soil salinity mapping in the Rio Mayo Irrigation District, Sonora, Mexico, over an area of about 100 000 ha, with an electromagnetic sensor and RS was completed in about six months. Two satellite images were used at an average cost of US\$0.35/ha. Figure 4 shows the salinity map of this irrigation district.

For areas where other factors in addition to soil salinity affect crop yield, Bastiaansen *et al.* (1998a and 1998b) developed a biophysical approach called the Surface Energy Balance Algorithm for Land (SEBAL). This approach is based on the determination of the spatial distribution of the leaf area index (LAI). This reflects the agronomic practices and the variations of stomatal resistance in crops, which are related to the retention of moisture owing to osmotic potential in the rootzone (which depends on the soil salinity). SEBAL requires visible, near-infrared and thermal infrared satellite measurements in order to compute the bulk surface resistance for a cropped surface and the LAI. This approach has been applied in several irrigated areas, e.g. in Uzbekistan (FAO/IPTRID, 2005), and in other countries as Egypt and the Syrian Arab Republic.

Research has been done on developing direct methods of measuring soil salinity through spectrum analysis, but they have yet to be applied in large-scale irrigation projects.

### **Drainage development in the studied area**

In many areas, the existing drainage systems consist of natural watercourses and main drains only. In such cases, a general description of the systems will suffice, highlighting the responsibilities and budgets of the involved public water management organization and the observed maintenance practices and conditions. However, where additional field drainage systems exist, it is necessary to describe the general technical characteristics of the existing surface drainage system (e.g. type, spacing between surface drains, and slopes) and of the subsurface drainage system (e.g. such as drain depth, spacing and drainage materials). In addition, information is needed on the availability of drainage materials and machinery, drainage costs, economic returns and



Source: Adapted from Pulido Madrigal et al., 2003a.

cost recovery. Information on implemented drainage tenders and the availability of private contractors for production of materials and implementation of drainage works is also desirable.

The environmental impacts of the existing drainage systems must be identified at this level as must the need for an EIA to be carried out in the following planning phase. The existence of water users organizations and their participation in existing drainage projects is one of the institutional aspects to be considered at this level.

#### **FEASIBILITY STUDY FOR PLANNING NEW DRAINAGE PROJECTS**

Once the problem areas have been identified, the feasibility of reclamation must be investigated and the new public drainage systems required in order to reclaim the affected areas can be planned. The feasibility study involves technical, environmental and socio-economic aspects to see whether the project is viable. Where this is the case, it is followed by designing the main drainage system or the rehabilitation, renewal of extension of the existing one, and by defining the characteristics of the individual field drainage systems.

The feasibility study of a drainage project is based on climate data, soil and hydrological studies, and additional information on land use and crops, natural vegetation, and, in irrigated lands, on irrigation water management (including supply

and quality aspects). Where some form of main drainage system exists, evaluation of its performance is required in order to assess the need for improvement. In addition, the environmental implications of the proposed systems and the socio-economic feasibility of the estimated investments (“with project” case) must be assessed against the situation that would develop were no project (“without project” case) implemented.

### Topography and land use

In the feasibility stage, existing topographic maps (scale from 1:10 000 to 1:5 000) that have significant information on existing irrigation and drainage, rural roads and other infrastructure are used. In flat areas, where most drainage projects are developed, the contour interval (which is the difference in elevation between contour lines on the final map), should be at most 50 cm, but a contour interval of 20–25 cm is desirable as this will be required at the design stage.

In this phase, land-use data provided by existing maps, usually at scale 1:50 000, are often not sufficient or they are outdated. Therefore, additional field information is required. Farmers’ information on crops and the cropping calendar, together with information on prevailing irrigation water supplies and availability, is essential at this stage.

### Climate data

The general information on climate and water balances is already known from the identification stage. For feasibility, more detailed rainfall information is required. The extreme values to be expected once in 2–10 years (for agriculture) or once in 100–200 years (for inhabited places) or human safety (1 000 years or more) should be known.

Annex 2 includes rainfall analyses for establishing design discharges by applying Gumbel’s method. Annex 23 provides the computer program for these calculations. More detailed information needed to calculate rainfall intensity is provided in Oosterbaan (1994). However, recent climate changes are tending to increase such extremes in many areas, and care is needed with such methods.

### Soil information

The areas affected by waterlogging and salinity can be defined more precisely than in the identification phase through a more detailed soil mapping at scale 1:10 000, with 5–10 observations per 100 ha. In this phase, the cost-saving physiographic approach can also be applied to map the main landforms if this has not been done already or if more detail is required.

In each landform, the soil characteristics required for drainage planning and further design are measured, especially:

- the permeability or hydraulic conductivity ( $K$ ) of the saturated soil;
- the infiltration rate ( $I_{inf}$ );
- the internal drainage of the soil and the characteristics of soil hardpans or other layers impeding water percolation where present;
- the transmissivity ( $KD$ ) (being the product of  $K$  and the layer thickness  $D$ ) of the layers down to any impervious barrier;
- the drainable pore space ( $\mu$ ) of the layer where the groundwater level oscillates;
- sometimes, the hydraulic resistance ( $c$ ) of a semi-pervious layer must be known, where vertically upward seepage from a semi-confined aquifer towards the rootzone is expected or where the reverse is true, i.e. deep percolation to deeper strata through such a layer.

There are often several soil layers in a profile, each with different  $K$ ,  $D$  and  $\mu$  values. They are denoted  $K_1$ ,  $K_2$ ,  $K_3$ , etc, and similarly for the  $D$  and  $\mu$  values. Moreover,  $K$  can vary in different directions (anisotropy) and, in cracking soils, it depends on soil wetness.

Field observations to describe soil texture, mottling, consistency and moisture content, depth of groundwater, and the thickness of the permeable layer, are made by manual auger holes down to some 2–3 m depth in mineral soils and down to 5 m in soft materials (e.g. peat). As high-cost deep borings (down to 10–15 m) call for mechanical augering, they should only be made where strictly needed. Where the groundwater level is below 1–1.5 m, soil profile descriptions from observations in pits are also recommended in order to describe soil structure (a relevant soil property related to infiltration rate, permeability and storage coefficient) and to observe the presence of layers that may hamper soil water flow processes.

#### *Permeability and infiltration rate*

The soil permeability and the infiltration rate are measured directly in the field. The values obtained should be related to soil texture and structure described through the soil observations.

The  $K$  values are generally measured by the auger-hole method. The piezometer method to determine  $K$  is less often applied. Annex 3 describes the field methods for measuring  $K$ . Programs AUGHOLE and PIEZOM to calculate  $K$ , whose principles are described in Annex 23, are included on the accompanying CD-ROM.

The infiltration rate can be determined using infiltrometers. The lowering of water in a ring is measured. The disturbance caused by lateral seepage is avoided by pouring water into two concentric rings and measuring in the inner one. Placed on the surface, the top layers are investigated, whereas the permeability of deeper layers can be measured at the bottom of a pit.

Conventional “single ring” and “double ring” infiltrometers have the drawback of only measuring a small area and, consequently, there is large variation between nearby measurements. Moreover, the soil conditions existing at the beginning of the experiment (wet or dry, crusted or not) have a great influence. Therefore, estimations from observations of the presence/absence of stagnation water after rainfall may be useful. The impact of raindrops can be mimicked by a rain simulator, of which various types are available.

In irrigated fields, more accurate values for infiltration into the top layers can be derived from irrigation evaluations, for example by comparing the curves of advance and recession of the irrigation water or by measuring the drop of the standing water layer of inundated plots.

The infiltration rate can also be used as an estimate for vertical permeability in granular soils. However, extrapolation of unsaturated hydraulic conductivity to saturated conditions in structured soils, where the saturated flow mainly occurs through macropores, is less feasible.

To reduce the effect of the spatial variability of the soil, it is necessary to obtain a series of data for each type of soil, from which an average value can be derived. In view of the large variability encountered in many cases, determination of the median value (which is easily determined) or the geometric mean of the soil characteristics is usually preferred to the arithmetic mean.

#### *Anisotropy*

The auger-hole and piezometer methods measure predominantly the horizontal permeability, infiltrometers measure vertical permeability, whereas the inverse auger-hole method measures a combination. However, alluvial sediments tend to be layered horizontally, with a vertical conductivity  $K_v$  lower than the horizontal component  $K_h$ , whereas  $K_v$  is usually higher than  $K_h$  in cracked clays because of the development of vertical fissures. Where the permeability varies in different directions, the soil is called anisotropic. In these cases, it is necessary to estimate an isotropic  $K$  value equivalent to

the actual anisotropic one. For clearly layered soils, a value of  $K_h/K_v$  of 16 is a better guess than neglecting the anisotropy, which means assuming a value of one.

Anisotropy is difficult to measure in the field because the usual methods provide the horizontal conductivity  $K_h$  only. The coefficient of anisotropy is defined by the relation between the horizontal and vertical conductivity of a soil layer. It can be estimated in a laboratory permeameter on undisturbed soil samples taken in both directions. However, as the size of the sample is usually small, the measurement can only be considered as an indication. A better choice is to compare the values obtained from infiltration tests (vertical) with those from auger-hole measurements (horizontal).

However, where this coefficient is known, drain spacing calculations can be made by using a model developed by Boumans (1979), to transform an anisotropic system into an equivalent isotropic one. This method has the advantages that the horizontal coordinates (such as drain spacing) remain constant and that multilayered soils can be handled. Annex 17 provides details on the application of this method.

This method is only applicable to vertical-horizontal anisotropy, which is widespread in drainage projects on alluvial soils. For other more complicated cases, it is necessary to refer to handbooks on groundwater flow (e.g. Childs, 1969; Raudkivi and Callander, 1976).

#### *Drainable pore space*

For non-steady drain spacing calculations, an additional input parameter is needed: the storage coefficient or drainable porosity of the soil. Direct field methods to determine  $\mu$  are available. For example, the method developed by Guyon (Chossat and Saugnac, 1985) based on the relationship between the volume of water pumped from an auger hole and the drawdown of the water observed in four piezometers installed close to the hole. However, direct field determination is difficult, cumbersome and imprecise. Therefore, the drainable pore space is usually estimated.

Quite good field estimates of the drainable pore space can be made from observations of the rise in groundwater level. The  $\mu$  value is the excess rainfall (expressed in metres or millimetres) divided by the groundwater rise (expressed in the same units) that would occur in the event of no discharge. Thus, a sudden rainfall of 20 mm giving a water table rise of 200 mm (without discharge) corresponds to a storage coefficient of 0.1. This method has been applied successfully in the Dutch polders, where  $\mu$  values of 0.10 and 0.03 were obtained for clay soils with crack development and for dense silt soils, respectively.

An alternative is measurement of the drawdown of the groundwater after heavy rain in cases where the discharge can be measured, especially in drained lands (see Annex 8).

Cylinder tests can be carried out, but have a limited representativeness. Therefore, the drainable pore space is often estimated indirectly from  $pF$  curves or from  $K$  values. Annex 4 provides some information about the relationship between  $\mu$  and  $K$ .

#### **Natural and present hydrological conditions**

Additional information is required on hydrological aspects, such as the recharge and discharge of the shallow aquifer, the discharge capacity of the existing main drainage system, and the options available to dispose of drainage water. Deeper aquifers are important if they are not completely confined. If under pressure, they cause upward seepage and often imply a considerable salt import into the rooted soil layers; if pressure is below the upper one, they contribute to drainage flows. All these conditions should be taken into account not only as quantitative aspects, but drainage water quality and the impact of disposal of drainage water on downstream water resources should also be considered.

Therefore, an integrated hydrological study is required in order to characterize the groundwater flow and its relationship with surface water under actual conditions before and sometimes after the drainage project. Where natural drainage is provided by a deep aquifer, it may sometimes be sufficient to render artificial drainage superfluous but its capacity may become insufficient if irrigation is introduced. If too much salty seepage is expected, the feasibility of the project is doubtful. Such future aspects associated with the project must be also considered.

### *Surface water study*

First, the available outlet conditions and the water level regime of the receiving waterbody must be considered. This is because every drainage project will fail without a proper disposal site for the water. The question is whether there are sufficient outlet possibilities or whether they should be improved or even created, e.g. by means of a pumping station. Chapter 5 describes the outlet and disposal requirements in detail.

The outlet water levels and the quality of the future receiving waterbody must be determined in at least two critical periods, i.e. during maximum flows (when the levels are highest) and during minimum flows (when the salt and pollutant concentrations are maximal).

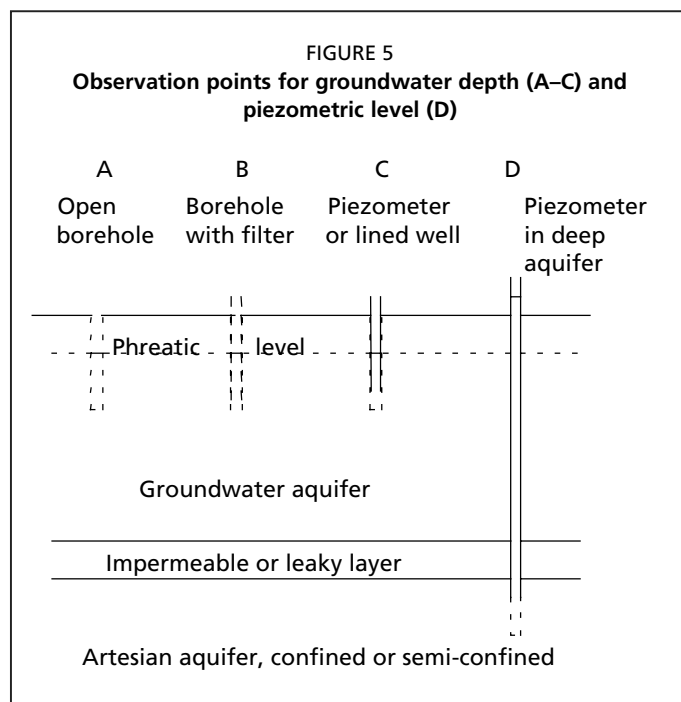
Second, the flow conditions of the existing open ditches and watercourses inside and around the project area must be known. The major issues to be considered are: the drainage conditions provided by the existing drainage network; the risk of flooding during the season of high flows (whether stemming from rain storms, periodic overirrigation customs or specific water management practices such as the release of the standing water layer of rice fields before crop harvest); and the relationship between surface water and groundwater.

Finally, the influence of watercourses, lakes and the sea (if nearby) on groundwater must be determined in order to assess the amount of seepage and to formulate the water balance in the project area. In coastal areas, the danger of salt intrusion into fresh groundwater must be investigated.

### *Shallow groundwater study*

An important item in the hydrological evaluation is the study of the shallow groundwater that the drainage system should control. The final product of this study is the isohypses map (isohypses being lines of equal water table height above a reference level). This map can be drawn once the hydraulic head data have been obtained by means of piezometric recording.

A piezometer, also known as a “lined observation well”, is a relatively short observation well provided with a closed standpipe to exclude influences from higher levels. Type C piezometers (Figure 5) are iron or plastic pipes with diameters of 25–50 mm. The bottom 10 cm are perforated and protected by a piece of cloth surrounded by



gravel or coarse sand. Type B observation wells are completely perforated pipes with a permeable envelope. These pipes are usually installed in a borehole with diameters ranging from 5 cm (in clay soils) to 8 cm. Type D piezometers, which generally have higher diameters, can also be laid by augering inside the pipe at 10–15-cm intervals and introducing the pipe afterwards. Thus, a good contact of the pipe with the surrounding soil is achieved. The high part of the buried pipe must be sealed with impervious clay to prevent leakage of surface water. About 30 cm of the pipe must be above the ground surface and tied to the soil with concrete. The upper end of the pipe is closed by a perforated plug to facilitate air circulation. The depth of the perforated area of the observation wells must exceed the usual lowest groundwater level.

Once the pipe is installed, groundwater is pumped and water levels are recorded in order to check whether the piezometer is working well. Once the installation has been completed, the elevation of the upper end is assigned by a detailed topographic survey, with reference to the mean sea level or a local basis level.

The main purpose of the isohypses map is to determine the direction of groundwater flow through the project and adjacent areas and its recharge and discharge zones. An isobaths map (isobaths being lines of equal depth of the water table below the soil surface) is sometimes needed to identify those areas where the groundwater table is above some acceptable threshold depth.

For a rapid reconnaissance of the groundwater flow in the feasibility stage, phreatic water level observations in the open boreholes (type A) drilled to obtain soil information are usually sufficient. However, in unstable soils (e.g. sands), type B is to be preferred. Water levels in existing wells and watercourses are also observed. All water levels are expressed in metres above or below the mean sea level (MSL).

Once the flow lines, which are perpendicular to the isohypses, and the recharge and discharge areas have been estimated on the draft map, more permanent observations of both B and C type are useful to measure the fluctuation of the groundwater level over a longer period. Type D pipes are needed for deeper aquifers, to find their possible influence on overlying layers.

Rows of observation points must be aligned along expected streamlines, but the exact location is not critical. For accessibility, it is useful to put them close to a rural road.

Detailed information can be useful:

- at the margins of the area, for flow towards or away from the project area;
- near existing watercourses, to see whether they are infiltrating or discharging.

The observation should be made perpendicular to these objects and in their neighbourhood.

The network density depends on: the level of the study, the complexity of the project area, and the resources available for drainage investigations. It may be low in the feasibility stage, but much denser in detailed studies for drainage design, where at least 5–10 piezometers per 100 ha are required.

From the soil elevation (for boreholes) or height of the top (for observation pipes) and the depth of the water level measurements, the hydraulic head can be calculated. Then, the isohypses map can be drawn by interpolation of the hydraulic heads between adjacent points, unless they are separated by discontinuities in landforms or in hydrology.

Different equipment is available to record the water level inside an observation well, ranging from flexible tapes with a special device to detect the water level by means of a sound or a light signal to submerged electronic water level recorders. Observation frequency depends on the groundwater level fluctuation. However, in climates with two distinct seasons, the recommendation is to repeat the observations in both the rainfall and irrigation periods. At least two records should be obtained in the shortest possible time interval, during the most critical periods of recharge:



- during periods of heavy rainfall, particularly if they coincide with critical phases of cropping (e.g. sowing or harvesting), when the need to ensure soil workability is a first priority.
- in the period of maximum irrigation requirements during the dry season or at the end of the irrigation season.

To support investigations regarding the detection of lateral seepage or deep upward flows, it is preferable to also measure the lowest water levels in a few selected observation wells.

The quality of the groundwater should also be assessed by taking water samples from the observation wells and piezometers. For the reconnaissance stage, quick measurements of the EC and pH may be done in the field. Alkalinity ( $\text{pH} > 8$ ) can be found as a pink colour on adding a drop of phenolphthaleine. However, full ion and pollutants analyses require laboratory support. Guidelines for groundwater sampling (including retrieval techniques) can be consulted in Smedema, Vlotman and Rycroft (2004). Details for fieldwork for sampling can be found in the guidelines drawn up by the United Nations Environment Programme (UNEP) and the World Health Organization (WHO) on water quality monitoring programmes (UNEP/WHO, 1996).

The final groundwater map should be checked with the topographic and geomorphologic maps in order to determine potential inconsistencies. The streamlines and the recharge and discharge areas can be drawn on the isohypses map. The hydraulic gradient can also be measured. In addition, where the  $KD$  values are known or estimated, the amount of lateral seepage through the borders of the studied area can be estimated by applying Darcy's Law. For the feasibility study, a rough estimate suffices.

### ***Geohydrological study***

Shallow groundwater is often underlain by an aquifer, which may be thin or hundreds of metres thick. This aquifer can be:

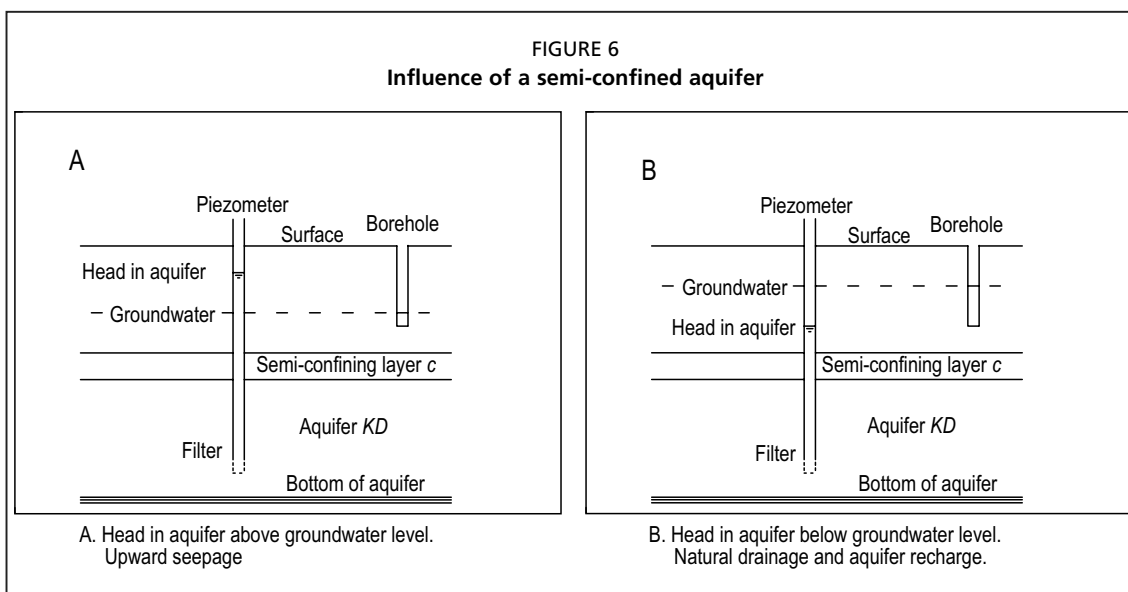
- unconfined, in open contact with the shallow groundwater;
- semi-confined, with a resistive layer in between;
- confined, without contact with the shallow groundwater;
- under pressure, where the head is above the phreatic level;
- artesian, where the head in the aquifer is above the land surface.

Where an unconfined or semi-confined aquifer is present below the shallow groundwater, geohydrological observations using piezometer batteries are required in order to determine whether there is upward or downward seepage from the aquifer or downward leakage towards it (Figure 6).

The magnitude and direction of the vertical flow depend on the hydraulic resistance to vertical flow  $c$  of the semi-confining layer and the transmissivity  $KD$  of the aquifer. These quantities can be found from pumping tests, which are described by Wesseling and Kruseman (1974), Boonstra and De Ridder (1994), and Kruseman and De Ridder (1994). Deep piezometers are installed above and below the semi-pervious layer in order to determine the vertical hydraulic gradient through the resistive layer (where the thickness of this layer is known). Annex 5 provides more details about these hydrological characteristics.

A piezometer network also allows the drawing of isohypses and isobaths for these deeper aquifers, to provide information about flow directions and heads. Comparison with the groundwater maps enables identification of the areas of possible upward and downward seepage in the present situation.

After the project has been executed, conditions will change. In newly irrigated areas, the aquifer may no longer be able to cope with the increased recharge. This may lead to rising groundwater levels in areas where natural drainage was initially sufficient. If the groundwater approaches the surface, waterlogging and salinization will follow. On the other hand, draining an area is usually followed by increased upward seepage. The



groundwater observation network should be maintained at strategic sites in order to evaluate the design after the system has been constructed.

Once the necessary data are available, the amount of seepage or leakage can be calculated by applying Darcy's Law. Detailed information on groundwater investigations is available in De Ridder (1994).

Geohydrological studies are not always economic as in some drainage projects the high costs derived from the placement of deep piezometers and performing pumping tests cannot be justified. However, sometimes they are badly needed, e.g. in the presence of karstic limestones, where there are possibilities of natural discharge.

### Hydrological conditions associated with the project

The need for artificial drainage may be assessed from a water balance in the saturated zone once the magnitudes of the inflows and outflows are known. For this purpose, in addition to percolation from the rootzone, the amount of seepage or natural discharge of the aquifer must be determined or estimated.

To determine the hydrological changes to be expected in the project area, it is necessary to follow an integrated approach. Improvements in the irrigation system and in the water management at the field level may reduce losses to drains and by deep percolation to aquifers, and consequently diminish the drainage needs and seepage problems. Costs and benefits of the different options of irrigation and drainage should be compared in order to select the most feasible solution.

### Water balance

An important item of the agrohydrological study is the formulation of a water balance considering the present and future conditions of the project area. From the observations of the present and future conditions related to the selected designs, a water balance should be drawn up, involving the following components:

- rainfall, snowmelt and irrigation;
- evaporation and evapotranspiration;
- surface runoff;
- infiltration;
- capillary rise to the rootzone;
- deep percolation from the rootzone, including leaching for salinity control;

- upward seepage from watercourses, higher lands and deep aquifers under pressure;
- downward seepage (leakage) to drains, rivers and deep aquifers;
- natural drainage or lateral seepage to lower lying terrains.

#### *Excess surface water*

Excess water (from rainfall, snowmelt and irrigation) that stagnates on the ground surface can be determined from the water balance of the soil surface. The excess should be discharged through the surface drainage system. For short periods, the evaporation is small and the excess depends mostly on input by precipitation and irrigation and output by infiltration into the soil.

Heavy rainfall is the main source of water stagnating on the soil surface. Chapter 6 describes a simple method to estimate the amount of excess surface water and the magnitude of the infiltrated rainfall based on the water balance. In addition to the infiltration rate, the data for extreme rainfall obtained by applying Gumbel's method (Annex 2) are the main inputs to formulate the water balance at the soil surface. Climate change often increases the frequency of extremes and, thus, may affect the results adversely. A separate analysis of the last 20 years is needed to check indications as to whether any recent changes have occurred (although this period is too short to confirm a climate change).

#### *Groundwater recharge by deep percolation*

Most of the water that infiltrates into the soil is retained in the unsaturated zone and taken up by plant roots. The remainder percolates and recharges the groundwater table. Thus, the water balance of the rootzone can be used to estimate the amount of recharge.

The recharge of the groundwater table can have different origins, i.e.: percolation of excess rainfall infiltrated into the soil, percolation of irrigation losses (including the leaching requirements), and upward or lateral seepage stemming from irrigation works or from higher lying surroundings. The opposite of recharge is loss caused by the reverse processes.

Percolation of rainfall water can be estimated from the water balance described in Chapter 6. In temperate regions, the annual balance is sufficient in most cases. Table 4 gives an example from the Veluwe area, the Netherlands. This area is formed by wooded hills on sandy soils, where irrigation is not practised and discharges are not visible.

Comparing the chloride content of the percolating water (9 mg/litre) with the rain content (4 mg/litre), the concentration factor gave a similar value of 2.2 (Meinardi, 1974).

In irrigated lands, the groundwater table is recharged by leakage from the system of water conveyance, by non-uniform distribution of the irrigation water and by deep percolation from the irrigated fields. Seepage from irrigation canals is described in the following section. Normal losses of irrigation water at the field level must be anticipated as they influence drainage requirements of the same field. If these losses penetrate into deep aquifers, they may cause increased seepage elsewhere.

The options to determine the amount of recharge caused by percolation of irrigation losses depend on the availability of data and the field information that can be collected in time and with reasonable costs. In irrigated lands, recharge can be determined from the water balances at the ground surface and rootzone (if other components of the balances are measured in irrigated fields). In new irrigation developments, the balances may be calculated at the design stage.

TABLE 4  
Example of annual water balance

Rainfall	800 mm
Evapotranspiration	450 mm
Recharge	350 mm

For planning purposes, average data from the literature are frequently used. Annex 6 provides details and examples of these procedures.

Percolation losses at the field level may be reduced by increasing the irrigation application efficiency. However, some amount of percolation is required in order to leach the salts accumulated in the rootzone. This fraction of water should be discharged through a subsurface drainage system if the natural drainage capacity is not sufficient. Therefore, in arid and semi-arid regions, the main purpose of drainage is to control secondary soil salinization.

In many irrigation projects, the amount of percolation from non-uniform application is enough to leach the salts added with the irrigation water. In overirrigated areas, it is possible to save water by improving the irrigation application efficiency while keeping the salt buildup in the rootzone under control.

However, in arid regions there is a trend to conserve water because it is becoming scarce. In these areas, additional water resources (groundwater, drainage water and treated wastewater) with restricted quality are being applied. Therefore, if more salts are added with irrigation and percolation is reduced, an accurate positive control of soil salinity is required. Moreover, the leaching requirements to maintain an appropriate level of salinity in the rootzone must be calculated, and the salt balance should be checked under these conditions. These requirements should be compared with the anticipated percolation in order, to ensure that water management (irrigation and drainage) is adequate to control soil salinity. Annex 7 provides technical details on leaching for salinity control and describes an approach for calculating the leaching requirements.

### *Seepage*

Lateral seepage from adjacent lands and leakage from watercourses through shallow layers is also a component of the recharge of phreatic aquifers. It is usually confined to the neighbourhood of these sources. More important and spread over larger distances is upward seepage from a deep semi-confined aquifer under pressure. Such pressure is caused by recharge elsewhere at a higher elevation.

New irrigation developments often cause additional excess water problems such as upward or downward seepage in areas where they did not previously occur. Leaky reservoirs and irrigation canals cause an extra load on drainage systems. These inputs should receive careful attention in order to predict future seepage rates. Strong upward seepage from the irrigation system as well as from higher areas can make drainage of waterlogged areas difficult or even impossible. In less severe cases, the increased seepage may be discharged through the drainage system without causing problems. However, where the seepage water is salty, even small quantities will deteriorate the water quality in the drainage ditches enough to make its reuse for additional irrigation impossible.

Drainage projects aim to lower groundwater tables in cultivated areas. However, in doing so, they may increase existing local or regional groundwater gradients. This may also lead to increased upward seepage in the project area.

Seepage from the network of irrigation canals may be reduced by improvements in the irrigation system itself. Under certain conditions, seepage can also be controlled effectively by interceptor drains. However, it is sometimes only partly controlled and the recharge related to seepage is a component of the total recharge to be controlled by contiguous subsurface drainage systems. The continuous losses of water resulting from leakage from irrigation canals depend on such characteristics as the canal size and whether the canal is lined or unlined. In this latter case, the permeability of the soil around the canal is the major factor affecting leakage, which is sometimes diminished considerably by siltation (self-sealing). Losses from closed irrigation pipes are negligible.

The amount of leakage from canals can be derived from local measurements. One method is to measure water flow in two control cross-sections upstream and downstream of the canal reach considered. The difference between inflows and outflows is the flow lost along the reach considered. This flow is usually expressed as a percentage of the water flow per kilometre of canal, but the method involves a difference between two difficult measurements with often similar values. A better method is to install two temporary dams at both sides of a canal reach, and to measure the recession of the ponded water level in between. The water loss is expressed in cubic metres per kilometre, and as a percentage of the normal flow. Data on leakage can also be estimated from the information provided in the literature, where general data of seepage losses (expressed as a percentage of the canal flow per kilometre) of lined and unlined main and lateral canals are provided (FAO, 1977b and 2002b). However, although it is difficult to obtain reliable local measurements, they are preferable.

### *Natural drainage*

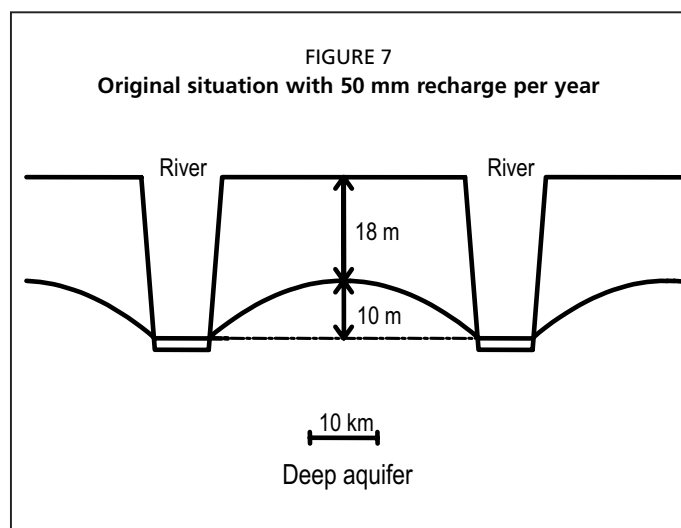
Potential outflows from the saturated zone are lateral flow through the boundaries of the project area and leakage through the semi-pervious layer (where present) to an aquifer that has draining properties owing to outflow elsewhere. The magnitude of seepage and of these components of the natural discharge can be estimated if a water balance is made and the groundwater levels are measured at different times or by following the procedures described previously in the geohydrological study and particularly those in Annex 5.

The existing aquifer capacity for natural drainage can be determined from the original situation. Some indication about natural drainage can be found by applying the method developed by Boumans, based on the assessment of the groundwater salinity, as described by Smedema, Vlotman and Rycroft (2004). A simple estimation can be made by measuring the fall of the water table in dry periods when there is no recharge and the water table is deep enough to ignore evapotranspiration. For example, if under natural conditions the water table is at depth of about 20 m and during a dry period of 200 days the drawdown of the groundwater level, measured in a deep piezometer, is 0.5 m and the  $\mu$  value of a sandy layer is 10 percent, then the amount of water discharged by natural drainage will be about 50 mm, i.e. 0.25 mm/d. If after the introduction of irrigation a recharge of 1 mm/d is expected, natural drainage will not be sufficient and some artificial drainage will be required.

The existing recharge can be estimated and the corresponding head measured. Because for deep aquifers both are approximately proportional, the future head can be predicted from the post-project recharge. Drainage will usually be needed, but not if the water table remains deep enough.

As an example, Figure 7 shows the original situation in an area in which the recharge is estimated at 50 mm/year.

After irrigation, the recharge increased to 200 mm/year, and the equilibrium groundwater level would become 40 m above the water level in the river, which would mean complete waterlogging. In reality, the groundwater rises about 1 m/year in this area. When it has come close to the surface, the water is removed by



capillary rise and evaporation, an upward movement that leads to salinization. A similar process has occurred elsewhere, e.g. in the Pakistani Doabs (currently irrigated plateau lands between intersecting rivers) and in part of the Nubaria Desert reclamation area on the West Bank of the Nile Delta in Egypt.

Where such processes are to be expected, artificial drainage will be needed in the future. Although this can be postponed for 10–15 years, it will become necessary. As such a system is costly, the need and global future costs must be estimated (albeit approximately) at the feasibility stage.

### **Crops and crop drainage requirements**

Once the natural conditions of the project area concerning climate, soils and hydrology have been determined, the next step in the feasibility study is to choose the appropriate cropping system adapted to the conditions foreseen after the drainage project implementation. It is then necessary to assess the requirements of the plants included in the selected cropping system as regards to ponding, rootzone waterlogging and to tolerance to soil salinity at the seedling, growth and harvest stages. Requirements for surface water and groundwater control relating to tillage and field trafficability associated with the cropping system are also needed in order to formulate land drainage criteria.

Concerning surface water ponding, the length of the critical period of crop inundation is the key issue. The period most critical is usually during spring and summer and in particular at the seedling stage. Ponding indices can be consulted in the literature (Smedema, Vlotman and Rycroft, 2004). Chapter 6 provides indications on the duration of critical periods for different crops.

Concerning control of waterlogging of the rootzone, the depth to the average highest water table midway between two drains is used for drainage design. Sieben (1964 and 1965) investigated an alternative method for the growth and production of notably winter wheat and barley. It showed that plant growth in the Netherlands is hampered by the duration and intensity with which groundwater levels exceed a crop-specific critical depth during the growing season. Similar conclusions were drawn from groundwater-level observations in sugar-cane fields in Peru (Risseuw, 1976).

The value of the desirable average depth to the water table or the critical time for groundwater lowering is usually inferred from local experience, expertise or literature. Simulation models, such as SWAP (Van Dam *et al.*, 1997) and DRAINMOD (Skaggs, 1999; Skaggs and Chescheir, 1999), can also be used, but they must be checked with local data. Local relationships between the average depth to the water table and crop yields and trafficability can also be estimated from observations in drained lands (Annex 9). Chapter 7 includes some indications on the desirable average depth to the groundwater table for different climate areas and crop systems.

Crop salt-tolerance information based on data by Maas and Grattan (1999) can be consulted in FAO (2002b).

### **Environmental procedures**

Chapter 2 has described the environmental problems and opportunities of drainage projects. The EIA of the drainage project and the mitigation plan should be prepared in this planning stage with the aim of controlling the environmental effects on adjacent areas, in particular those situated downstream of the drainage outlet, and the negative impact of the drainage works in the project area itself.

Some specific items of EIAs and mitigation plans include:

- soil salinization and soil conservation;
- hydrological changes in downstream flow peaks, duration and low flows either as related to the existing conditions or as agreed upon;

- hydraulic issues, such as stability of outlet channels, sediment control, capacity of evaporation ponds, constructed wetlands, stabilization ponds and water treatment facilities;
- impacts of the hydraulic works on the landscape;
- water quality aspects, namely, salinization and pollution potentials and the protection for receiving bodies of water in line with agreed standards;
- saltwater intrusion into surface waters caused by open drainage outlets or river mouths (especially under tidal conditions), or into groundwater by excessive pumping from wells;
- impacts on existing wetlands, protected areas, and nature reserves situated nearby or downstream protected areas where changes in the water regime may alter the existing conditions;
- health factors related to water-borne diseases and sanitation requirements;
- social considerations, such as safety of the population during and after construction, relocation of individuals and facilities.

Any adverse effects should be compensated as much as feasible, and the needs and global costs of such mitigation plans must be assessed and included in the economic assessment of the project.

The EIAs for drainage systems are particularly critical owing to the wide range of the potential environmental issues described above. Designers must use the various details noted during the planning process in order to be certain that the facilities are in line with stakeholder expectations. The process for EIA preparation and discussions about the major environmental impacts of irrigation and drainage projects has been described by FAO/ODA (1995). This FAO Irrigation and Drainage Paper includes guidelines for preparing terms of reference for EIAs.

The feasibility report should include these environmental requirements and mitigation plans in its recommendations for the design stage.

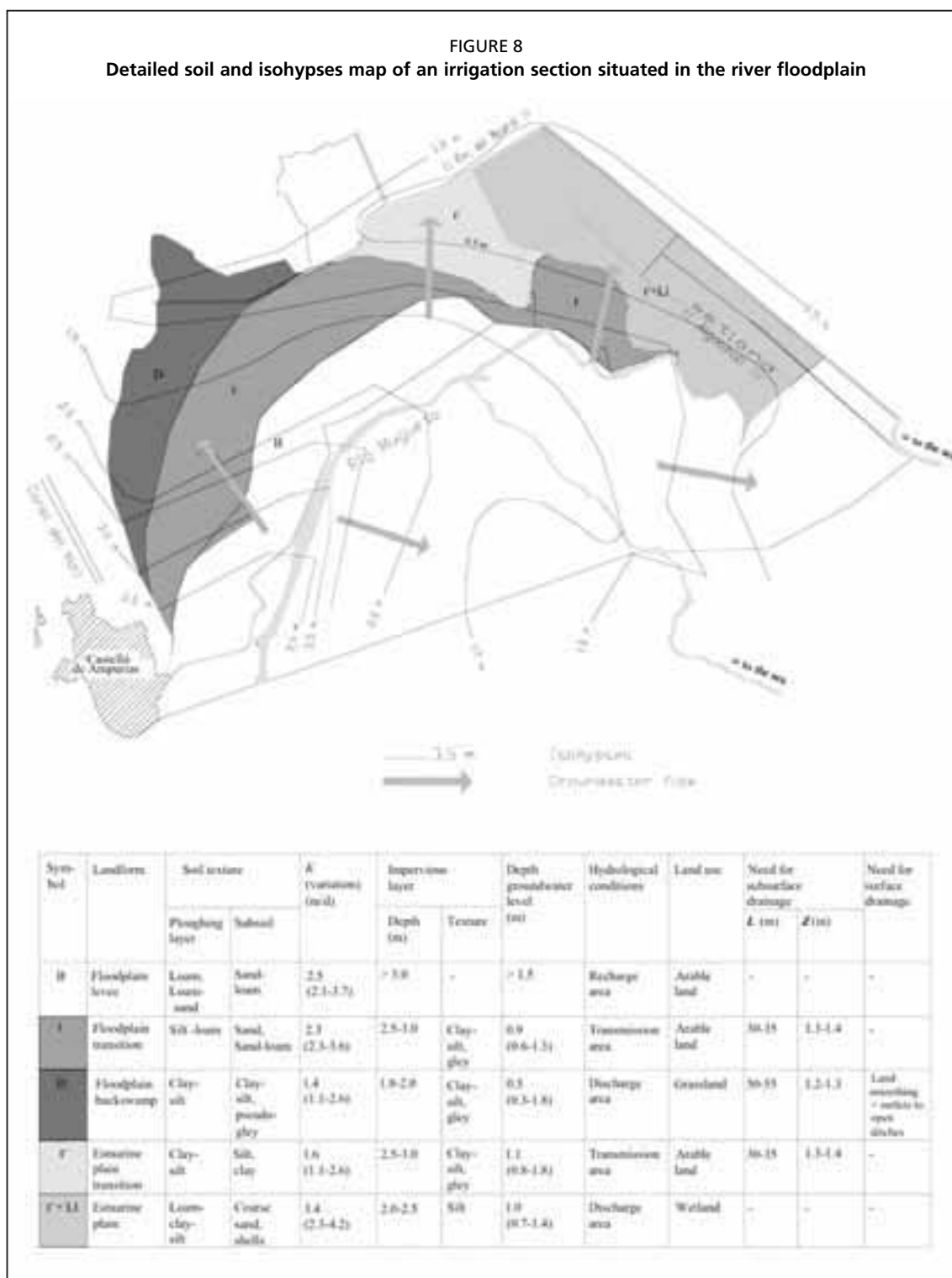
### **Socio-economic evaluation**

Governments and financing organizations require a socio-economic and financial evaluation of the drainage system planned in order to enable them to assess the overall feasibility of the project. At this stage, this can be done by comparing benefits with costs and by calculating the internal rate of return (Chapter 3). With regard to the assessment of the social impacts, a descriptive or comparative approach is preferred in order to evaluate the impact of the drainage project in comparison with the situation that would develop if no project were implemented.

The USBR recommends a simple method to estimate the benefit/cost ratio (USBR, 1984). Capitalized benefits over the life of the drainage system (100 years in USBR projects, at the current interest of capitalization considered) are compared with total costs, i.e. the costs of the system plus the estimated O&M costs. If the project area is cropped and drainage contributes to increase land productivity and ensure agriculture sustainability, the opportunity cost of the actual benefit without drainage must be considered in comparison with the drainage costs. In areas where the actual land productivity is negligible, such as with saline soils, the total value estimated for the future agricultural production is taken into account. In irrigated lands, in addition to the drainage costs, the irrigation costs should be included in this analysis. Drainage projects with a benefit/cost ratio greater than one are generally considered economically feasible. This method is useful for preliminary estimations made by drainage engineers. More complete economic and repayment analyses are required for large-scale drainage projects.

### Example of the planning at feasibility level of a new drainage system in an irrigation sector

As an example of output of the soil and hydrological investigations described in the above sections, Figure 8 shows a simplified map of an irrigation section with the soil types and the isohypses map superimposed.



Source: Adapted from IRYDA, 1989b, and Martínez Beltrán, 1993.



From the map legend, it can be observed that no artificial drainage is required for the lands of the levee of the floodplain (B) because they benefit from natural drainage, the groundwater level is below 1.5 m and the soils are salt free. The isohypses map shows that groundwater is flowing from the river (the recharge area) through the aquifer below the levee towards the backswamp. On these lands, maize, wheat and sunflower are cropped on a sustained basis.

However, the soils of the transitional area between the levee and the backswamp (t) are affected by salinity because the groundwater level is frequently shallower than 1.3 m. To obtain a sustainable agriculture in these lands, similar to the levee lands, a subsurface drainage system is required in order to control the groundwater level and to discharge the salts leached by percolation water.

Natural drainage is even more restricted in the lowlands of the backswamp (D) and in the transitional areas to the estuarine plain (t'). The soils are fine textured, hydraulic conductivity is lower and the groundwater level is permanently above 0.8 m, stagnation being frequent after heavy rainfall. In this area, a surface drainage system is required in order to discharge excess rainfall and a subsurface drainage system is needed to control the groundwater level, if farmers wish to grow field crops and even if they wish to improve the existing grassland.

The estuarine plain (LL) is currently a wetland with silty saline soils. These are generally waterlogged owing to persistent shallow groundwater levels. As this land use must be maintained as a natural reserve, there is no need for artificial drainage in this area. However, as the main outflow drain, which conveys the drainage water from the agricultural lands, runs along this reserve, management of the drainage water quality in the adjacent agricultural area is an essential component of the planning phase and of the subsequent normal operational of this project.

Figure 9 shows the map of the irrigation section where drainage problems were identified and characterized in the previous stages (left bank of the Mugueta River shown in Figure 8). It can be observed that only some open ditches are situated in the low-lying areas identified in Figure 8. The drainage water is conveyed to the outside drains (rec Cagarrel and rec Madral). The studied area is protected from flooding of the outside drains by means of small dykes. In the highest part of the studied area and during the dry period, water is discharged in the outside drain (rec Cagarrel) by gravity, but pumping is required in the lowest part (rec Madral), especially after heavy rainfall.

However, there are no field drainage systems. Therefore, it is necessary to design new systems for the areas lacking natural drainage, and to complete the existing main drainage system with collector drains to convey the surface runoff and subsurface flow discharged by the new field drains.

An essential factor to be considered in this planning stage is the environmental impact of the irrigation section on the natural reserve, especially concerning the quality of the drainage water to be disposed in the outside drains. Consequently, the recommendation was to maintain grassland use (free of agrochemical applications) in the low-lying areas of the backswamps, with improved surface and subsurface drainage and controlled water levels.

Once the areas with different land-use and drainage needs have been mapped and their specific hydraulic characteristics have been determined, drainage requirements and costs can be assessed. In the legend to Figure 8, it can be observed that, at the feasibility stage, subsurface drainage requirement in terms of drain spacing (L) and depth (Z) are determined for each type of soil. This is done on the basis of the average values of their hydraulic characteristics and the drainage coefficients determined for the planned land use. In the backswamp areas, in addition to subsurface drainage, land smoothing and surface drainage outlets are required in order to remove excess rainfall.

The benefit/cost ratio estimated for the transitional lands between the levee and the backswamp areas (t) (where agricultural production could be similar to the production



obtained in the levee lands (B) if groundwater levels are controlled) was about 5:1, considering an annual interest rate of 5 percent and 100 years of economic life of the subsurface drainage system. The benefit/cost ratio for improved grassland in the backswamp areas (D) was about 2:1.

In summary, the technical and economic feasibility of the drainage systems planned was confirmed. The environmental feasibility would also be positive if sound management of the water quality of the drainage water could be achieved.

#### **DETAILED STUDIES FOR DRAINAGE DESIGN**

Once the feasibility of the project has been established, the final design is made, either for a section or for the entire project area. At the beginning of this phase, consideration should be given to a stepwise implementation approach of the necessary project works.

This is especially important where the inferred causes of the drainage problems include inadequate water level management in the main public drainage system and/or irrigation water management practices at public system level, which generate unnecessary irrigation and rainstorm surface runoff. Rehabilitation and restoring sufficiently deep water levels in a main drainage system and/or reduced irrigation water spill losses may well reduce expensive field drainage requirements in areas with pervious subsoils, as well as avoid the construction of oversized pumping stations.

During the design and execution stages precise, topographic maps are indispensable. There should be a special focus on the careful measurement of the land elevation and on providing detailed information on the irrigation and drainage systems existing at the project area. The scale most frequently used in drainage projects for areas of 100–300 ha is 1:5 000, but scales of from 1:2 000 to 1:10 000 are also used depending on the size of the project area. On maps at a scale of 1:5 000, the common contour interval is 20–25 cm, but 10 cm might be required in extremely flat lands and 50 cm can also be worked with in sloping lands. Where no detailed maps are available and the survey is too expensive to base the design on the existing maps, once the first design is completed, the levels in the drain lines and collector lines must be measured in detail (one point every 20–25 m) and the design adjusted as necessary.

Figure 9 shows an example of topographic information. In addition to the contour lines separated each 50 cm, this map shows the existing irrigation and drainage systems (and the road network).

At the design stage, the first action is to identify precisely the outlet site and to select the type of disposal structure. Then, the layout of the new main drainage system is determined. Where only supplementary drains are required, they are inserted in the existing network. Later, the field drainage systems are designed. However, in order to determine the dimensions of the main drains, the surface and subsurface drainage coefficients must be known.

The outlet site should be located in the lower part of the project area, as identified in the topographic and isohypses maps. At this site, the average and maximum outside water levels must be determined. By comparison with the design inside water levels, the type of outlet structure (gravity, tidal gate or pumping station) is chosen. In addition, the discharge and water quality regime in the receiving waterbody must be known in order to design the water quality management practices to reduce the environmental impact of drainage water disposal.

Chapter 5 and Annex 10 describe the basic concepts and hydraulic formulae that are required for detailed design of the components of the main drainage systems, including auxiliary and outlet structures. Chapter 8 and Annex 23 describe a computer calculation program for determining the backwater effects on the main drainage system.

Surface drainage systems are described in Chapter 6, with details on methods to estimate the design discharge in Annexes 11–16.

For subsurface drainage, the first decision is whether to follow a steady-state or a non-steady-state flow approach. The former is easier and usually sufficient, but the latter may be necessary for sensitive crops under heavy rainfall, and for irrigated high-value crops in arid and semi-arid regions. In any case, the critical period or season should be defined as this is when groundwater and/or soil salinity conditions usually have their most negative impact on crop production.

The criteria for the steady-state flow approach are:

- The design discharge (in millimetres per day) is usually the same for an entire project or large parts of it.
- The desired groundwater depths under critical conditions. They may differ for different cropping systems.

For the non-steady-state flow approach:

- The critical time of ponding (especially for sensitive crops).

- The required lowering of the groundwater within a given time after the soil profile has been saturated by a heavy irrigation turn or rainstorm.

Chapter 7 and Annexes 17–19 describe the principles for detailed subsurface drainage design, including drainage equations and drainage design criteria. Computer calculation programs are also described in Chapter 8 (in more detail in Annex 23).

Once the drain depth has been selected, drain spacing is calculated by applying, in the most appropriate equation and in the specific computer program, the design criteria and the average values of permeability and thickness of the pervious layers. In non-steady-state calculations, the value of the drainable porosity is also used.

Detailed studies are now required, especially for those that have a profound influence on drainage design, i.e. the drainage design criteria and the soil hydraulic characteristics: the hydraulic conductivities; the thickness of the permeable layer (or layers); and – in the non-steady case – the storage coefficient. Soil stability estimations at design drain depth are also important for predicting the need for drainage envelopes or special drainage installation techniques. As they often vary considerably, detailed observations are required, e.g. one per 5–10 ha, depending on the spatial variability.

At a detailed level, less use of photo-interpretation is made. However, soil maps (from 1:5 000 to 1:10 000) based on landforms are also used. These comprehensive maps are much more convenient than thematic maps with contour lines for each characteristic.

Care must be taken in the design phase to consider the environmental issues identified in the planning phase and to develop designs that follow the agreed environmental plans.

Considerations on future maintenance needs must be taken into account at this stage as the institutional setup of maintenance has its consequences for the designs (see Chapter 3).

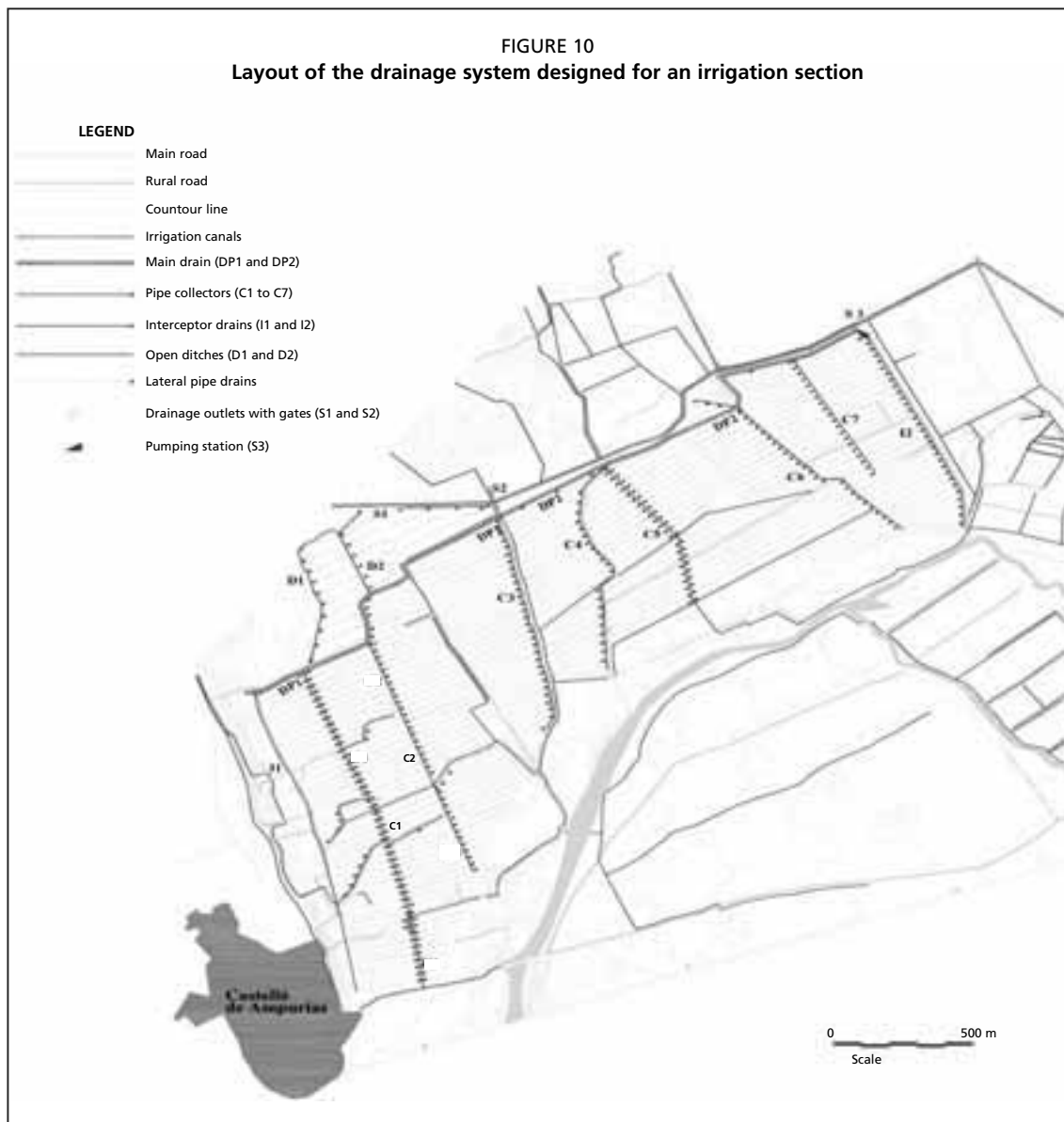
The project document should further include:

- a short text making reference to the outputs of the planning phase, in particular to the design criteria;
- annexes with calculations of the parameters of the different components of the system;
- the environmental mitigation plan;
- the detailed designs of the drainage works on the basis of the foregoing criteria;
- maps with the layout of the system and the start and end level of each drain or section of drain;
- the necessary appurtenant works, such as bridges, weirs, sluices and pumping stations;
- a bill of quantities of the materials needed;
- the technical specifications and procedures for implementation of the drainage works;
- the construction costs assessment;
- the O&M costs in relation to the organizational aspects of its implementation;
- where applicable: special irrigation development and/or crop husbandry practices to be adopted in order to meet specific environmental requirements in relation to the disposal of drainage water to downstream areas.

### **Example of a map with the layout of a designed drainage system**

Figure 10 shows the drainage system designed to control waterlogging and salinity in the problem areas of the irrigation section mapped in Figure 9.

Figure 10 shows that a subsurface drainage system with laterals laid at an average depth of 1.4 m and spacings of 30 m plus seven pipe collectors (C1–C7) has been designed in order to control waterlogging and soil salinity in most of the left bank of the Río Mugueta floodplain.



In the low-lying backswamp, subsurface drains have been designed at an average depth and spacing of 1.2 m and 50 m, respectively. In this area, the existing open drains (D1 and D2) are retained in order to receive surface runoff in addition to the subsurface drainage discharge.

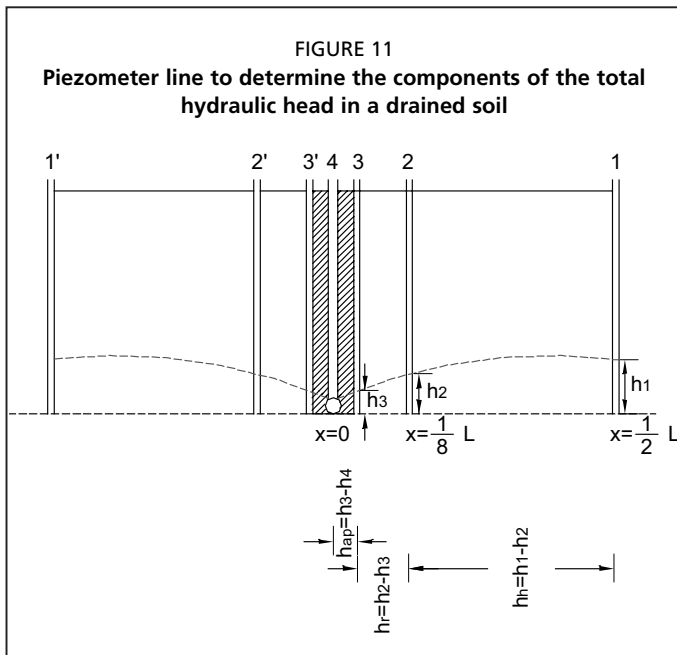
To cut off seepage from adjacent high-lying areas and from the nature reserve, interceptor drains (I1 and I2, respectively) have been designed. The latter will also function as the collector drain of the affected laterals.

The existing main drain (DP1) is retained as are the existing gravity outlets to the Cagarrel outside drain (S1 and S2) in order to dispose of subsurface drainage water during most of the year, especially during the irrigation season. However, a new main drain has been designed (DP2) to collect the drainage discharge from pipe collectors C4 to I2, and surface and subsurface runoff of the whole irrigation section, when gravity outlets S1 and S2 are not able to dispose of water because of outside high water levels during peak water flows. Therefore, DP2 ends in a pumping station located in the lowest point of the project area (S3). During periods of extreme rainfall, water could be pumped from this station to the Madral outside drain with a direct outlet into the sea.

Once the drainage works have been implemented, M&E systems are needed to verify whether the systems are operating physically, environmentally and socio-economically as planned and designed. Monitoring plans should be developed as designs are being prepared, and the evaluation system must relate directly to the items to be monitored. The evaluations must be made in a timely manner so that adjustments or additions can be made where potentials for environmental or physical degradation are noted.

**INVESTIGATIONS IN DRAINED LANDS**

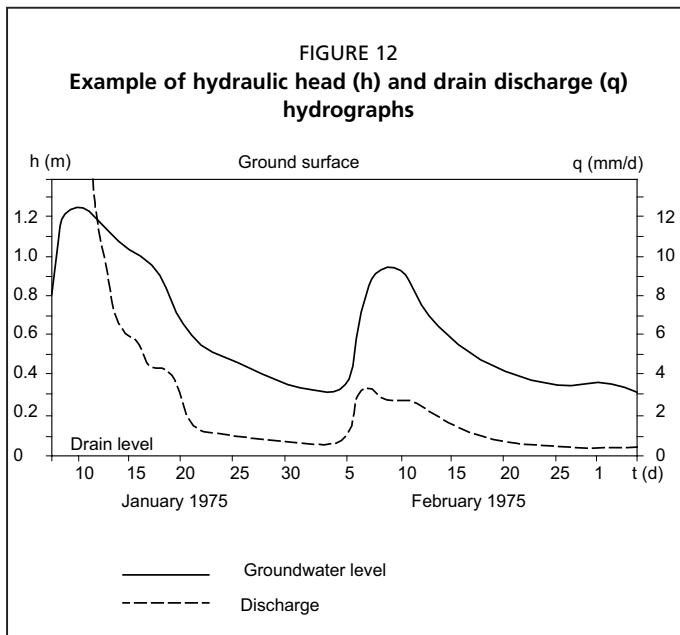
In already drained lands, investigations focusing on the relationship between drainage discharge and hydraulic head are useful for deriving soil hydraulic characteristics for a specific type of soil. In this case, a large volume of soil is contributing to the outflow of the drains, in contrast to the small volume investigated by the methods described in the previous sections.



The specific discharge is calculated from the drainage flow measured at the drain outlet. The different components of the hydraulic head required to overcome the different resistances to the subsurface flow towards the drains can be measured by means of piezometer readings in tubes laid at different distances from the drain, as shown in Figure 11.

Annex 8 provides details on the procedures for determining the hydraulic conductivity, the radial resistance and the drainable pore space in drained lands.

Measurements of drain discharge in drained areas are also useful for determining drainage coefficients under actual conditions. Discharge hydrographs (Figure 12) can be used to assess the peak discharge and the average drainage coefficient during a non-steady-state drainage period.



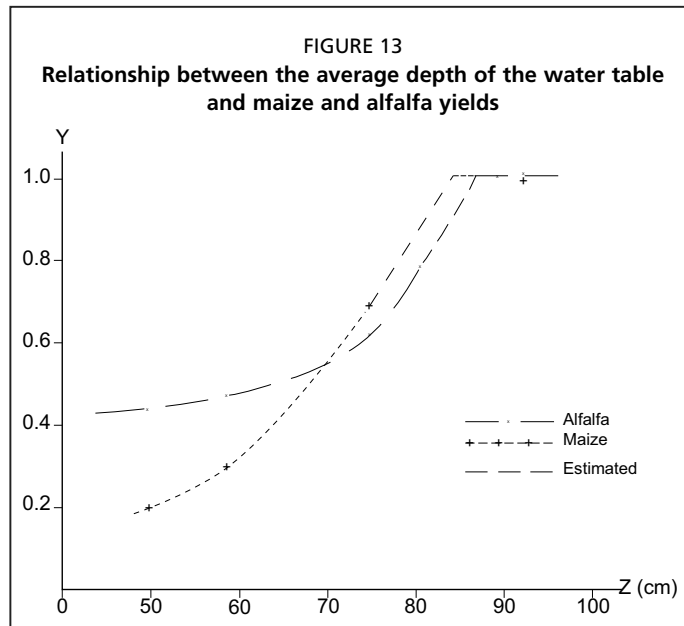
The relationship between the depth of the groundwater level and crop yields and wetness conditions of the top layer affecting soil trafficability is also useful for estimating the optimal depth of the groundwater table. For example, Figure 13 shows the relationship between the relative yield (Y) of maize and alfalfa and the average depth of the water table (Z). It indicates that an average depth of 85 cm might be critical for these crops, although temporary shallower

Source: Adapted from Martínez Beltrán, 1978.

depths are tolerated by most field crops, e.g. 30 cm in one day.

Annex 9 provides additional details on procedures for assessing drainage criteria in drained lands.

In summary, sound drainage design criteria can be formulated for new projects with similar characteristics to those of the observed lands. In recently drained areas, the basic data used for drainage design can be checked in the same way. If the performance of a newly installed drainage system is monitored as early as possible, the resulting information can be used to adjust the partly estimated  $KD$  values and drainage coefficients for similar areas still under construction.



## Chapter 5

# Main drainage and disposal systems

### INTRODUCTION

In any project involving land drainage, it is advisable to work from the downstream part of the system in an upstream direction, that is:

1. It is necessary to provide a suitable outlet for the drainage water, either by gravity or by pumping.
2. If this outlet alone is insufficient, a main system of open drainage channels and ditches must be constructed to convey the drained water to the outlet (in this chapter, channel indicates an open drain that is of larger dimensions than a ditch, whereas canal is used specifically for irrigation).
3. If this main system cannot provide adequate control of groundwater levels in the fields, a system of field drains is needed, forming a detailed drainage system, consisting largely of subsurface pipe drains. Chapter 7 describes such subsurface drainage. Open trenches are sometimes used for groundwater control instead, e.g. in drainage of heavy land and in the humid tropics. However, the use of open trenches for subsurface drainage is not generally recommended, as they hamper agricultural operations, reduce the cultivable area and increase the maintenance burden.
4. If these field drains are still not able to cope with water stagnating on the surface, additional measures (e.g. raised beds with superficial ditches or landforming) should be taken. Chapter 6 describes such surface drainage.
5. The division between public main open drainage networks and detailed open subsurface drainage systems is somewhat arbitrary. Ditches serving a few land users are sometimes classed with the former and sometimes with the latter depending on local circumstances, traditions, and direct responsibility for maintenance.

Where any element of the main drainage system is not functioning properly, all upstream facilities cannot fulfil their purpose. Thus, a good outlet and a well-designed and well-maintained main drainage system are prerequisites for adequate field drainage.

Apart from these features dealing with the removal of a certain quantity of drainage water, the quality of the drainage water should also be considered. Within the project area, water quality governs the possibility for its reuse for irrigation, and outside downstream users and downstream ecology may be affected. These quality aspects are becoming increasingly important in drainage projects. Therefore, the layout of the system must minimize its negative environmental impacts.

Chapter 2 has considered briefly the quality aspects of drainage waters. The FAO Irrigation and Drainage Paper on the management of agricultural drainage water in arid and semi-arid areas (FAO, 2002b) considers these factors in detail.

This chapter focuses on the main system, first providing a general description and then adding design requirements and criteria. Annex 10 provides technical details for calculations.

Programs for tree-shaped systems with steady flow, based on the Manning formula, are available at many institutions, waterboards and engineering firms. An example is the HEC-2 program developed by the United States Army Corps of Engineers (USACE,



1990). For non-steady-state flow and network structures, more sophisticated methods are needed, such as the program DUFLOW (STOWA, 2000), based on numerical solutions of the Saint Venant equations, and the HEC-RAS program, which has been adopted by the United States National Resources Conservation Service. Details on these programs, including procurement addresses and Web sites, are given in Smedema, Vlotman and Rycroft (2004). In this paper, the program BACKWAT (Annex 23) describes backwater effects.

### STRUCTURAL ELEMENTS

Where the position and hydraulic characteristics of the outlet are known, the following decisions are of concern in the layout and design of the various elements of the upstream system.

The layout will be considered first, followed by a description of the various structures belonging to the main drainage system, such as:

- channels and ditches – they require alongside facilities (tracks, agreements with adjacent land users / landowners) for inspection and maintenance;
- bridges and aqueducts;
- culverts and siphons;
- weirs and drop structures;
- sluices, gates and main pumping stations at the outlet, or any intermediate pumping stations may be considered to belong to this category because they form part of the outlet works.

Attention is needed in order to prevent bank erosion, especially at points where surface runoff collects or field drainage systems are connected with the open channels of the main system.

### Layout

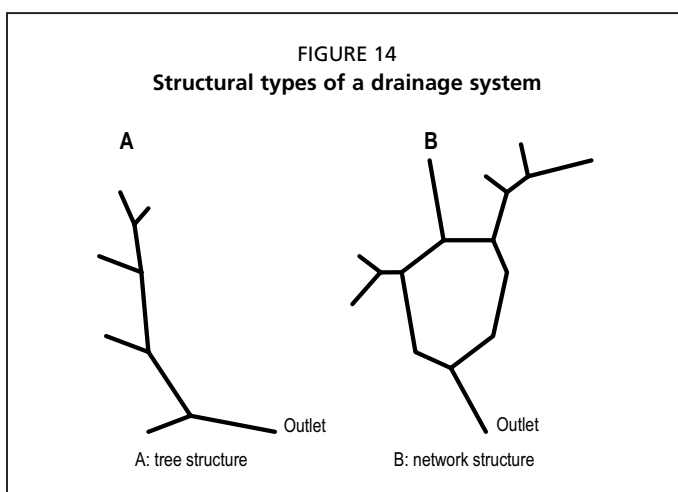
The projected main drainage system usually has a branching-tree configuration (Figure 14) in which every drop of drainage water has only one way to reach the outlet. However, more complicated network structures are sometimes found, usually remnants from former natural drainage systems.

The network depends greatly on the size of the area, its topography, the existing watercourses and the form of its borders. In a system composed of buried field drains, collector pipe drains, ditches and larger waterways, the length of each successive order determines the distances of the next. Thus, the distances of the first open channels (usually ditches) depend on the lengths spanned by the subsurface drainage system. There is a tendency to replace the first open ditches with buried pipes, thus reducing

the density of open waterways and consequently saving on maintenance (a costly operation).

Another element for the choice of layout is the future maintenance of the main system and its organization. The smaller elements can be maintained by a farmer or a local farmers group, be it by hand or by machine. The larger elements can be maintained mechanically by an organization in which the stakeholders participate and can have indirect influence, e.g. a water board.

Within the project area, there



may be protected natural reserves. These should be left untouched by the main drainage elements. The channels should keep enough distance from these areas to avoid influencing the underground water currents to and from the reserve area. Opportunities for improving ecological values sometimes exist in important areas not protected as reserves. Some special drainage with water table management may improve the habitat or ecological values considerably. These potential options should be discussed with stakeholders.

Villages and towns and agriculture-based industrial zones in the project area are best provided with a dedicated connection to the public main drainage system to facilitate controlled disposal of polluted water and minimize the risk of improper reuse. Where possible, such urban waters should be treated.

The location of the drainage channel network depends on the topography. In undulating terrain, the watercourses follow the valleys and, thus, the pattern is irregular. However, in flat land, a rectangular layout is usually designed, with exceptions owing to the shape of the project boundary and natural watercourses, or to slight differences in elevation. Existing waterways are often enlarged, but sometimes they are replaced by a new and wider spaced network of larger channels. These channels should follow the natural drainage paths where possible.

As layout and location of elements are highly determined by local circumstances, it is not possible to give more detailed information about these points.

### Channels and ditches

Open waterways or channels form the principal part of a system that conveys the outflow from the fields to the outlet. There are two types of layout (Figure 14):

- a tree structure, where this path is fully determined (e.g. from ditch via a small watercourse into an ever larger one, until the outlet is reached);
- a network structure, in which more than one route is available and where the path depends on the local gradients. The branches of such a network are cross-connected (anastomosis).

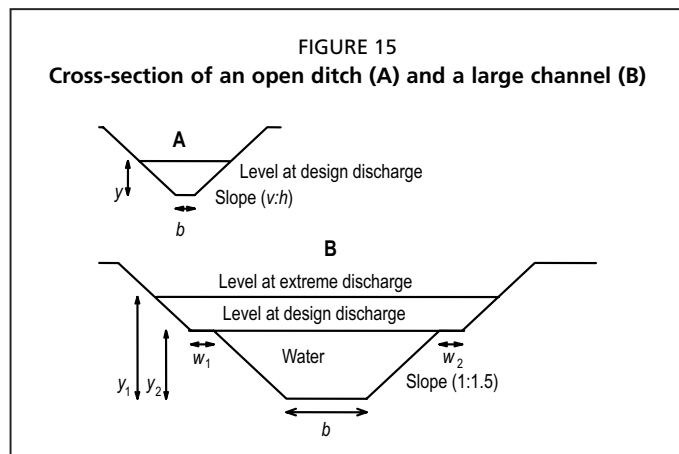
Networks, such as the elaborate system of channels of the Mekong Delta, are beyond the scope of this publication as this type is seldom used in new projects. Special calculation methods for flows through networks are available, but they are complicated.

In most projects, the tree structure is chosen and a straightforward method of calculation is allowed.

The cross-section of open channels (Figure 15) is usually trapezoidal for small drains, and sometimes with a double trapezoid for larger ones.

The side slopes are indicated in this publication as the ratio of vertical to horizontal ( $v:b$ ) and depend mostly on the type of soil (see Table A10.2). Some points to consider are:

- Steep slopes save on excavation costs, and such channels occupy less agricultural land, but slopes that are too steep result in bank failures.
- Local experience is the best guide for safe channel side slopes.
- Any slope failures usually occur shortly after construction – later, the bank vegetation has a stabilizing effect.



- Vegetation (especially submerged plants) obstructs the water flow. Thus, regular maintenance is required. In particular, woody vegetation on the banks must be kept short.
- Lateral groundwater seepage promotes slumping of channel banks. In places with strong seepage, it is necessary to either adopt flatter slopes, provide suitable vegetation cover, or cover the banks with permeable but heavy materials. Geotextiles covered with loose stones are useful in such cases.
- Trapezoidal profiles are designed and built. However, after many years, they change into more parabolic forms, often with steeper slopes above the usual water levels, covered by vegetation kept short by mowing. In areas with arid climates, the vegetation remains sparse and is confined mainly to the area near and below the water line.

The ratio of water depth ( $v:b$ ) to bottom width ( $y:b$ ) should be kept between certain limits (see Table A10.1). The calculation of the expected flow rates for the assumed channel dimensions and gradient is based on Manning's formula (Equation 1 in Annex 10). Where the calculated flow rate is too high, the calculation should be repeated with a milder gradient and/or a different  $y:b$  ratio.

Erosion in watercourses should be avoided. At design discharge, the flow velocity must be limited to safe values (see Table A10.2). At low flows, meandering of the small remaining stream must be prevented as it can undercut the banks. Both can be achieved by placing weirs at appropriate points, so that sufficient water depth is maintained. Another option is to limit the bottom width of the ditch. This is helpful if weed growth is expected to increase with weirs owing to shallow water depths during extended low flow periods. Parabolic ditch bottoms or small base flow drains in the ditch bottom area have also been used successfully in some cases. Special attention is needed at places where elements of the detailed field drainage systems spill into open waterways (Chapters 6 and 7).

Open drainage channels need regular maintenance. This is because they are susceptible to choking by the growth of aquatic plants and silting up by sediments brought in by uncontrolled surface runoff. In contrast to most irrigation canals, which carry turbid waters, plant growth in open drains is more intensive. In large channels, a water depth of at least 1 m (1.5 m is better) will hamper the growth of reeds, although submerged and floating plant species may still thrive. In ditches, growth is retarded where they periodically fall dry. A minimum cross-section is often prescribed in order to secure sufficient discharge capacity, especially for small waterways (which may become rapidly overgrown with weeds). Such a minimum cross-section has a bottom width of 0.5–1 m and a water depth of 0.30–0.50 m at design discharge, and preferably zero in dry periods. These dimensions can vary according to the machinery available for construction and maintenance.

Although these measures are of some help, periodic maintenance is always needed, especially before the onset of the season in which drainage requirements are highest (usually the end of the wet season; in the case of rice in arid regions it may be the pre-harvest period). Special equipment is available for mechanical cleaning of these open watercourses. This equipment is specific for two maintenance operations: desilting and dewatering. When cleaning an open drain, care should be taken to avoid making the side slopes steeper – so reducing the risk of bank failure.

### **Bridges and aqueducts**

Where roads and railways cross main waterways, bridges are needed. Irrigation canals usually cross by means of aqueducts. Those that leave the cross-section of the waterway intact have no influence upon the flow in the channel. However, if they are narrower, notably in flat areas, special formulae for flow through openings are used

to limit backwater effects (Equation 6 in Annex 10). Erosion of the channel under the bridge should then be avoided by not allowing high flow velocities.

### Culverts

Culverts are necessary where an open drain crosses a farm entrance or a rural road. One metal, concrete or reinforced plastic pipe buried at least 50 cm deep is commonly used where the water flow is less than 0.5 m<sup>3</sup>/s, and two such pipes for discharges up to 1 m<sup>3</sup>/s. Their diameter depends on the amount of flow and on their length, but a minimum diameter of 300 mm is often recommended in order to facilitate cleaning. Where the flow is higher, large-diameter pipes, box-type culverts or bridges are used.

Calculations for culverts are based on the hydraulics of flow through openings and friction in pipes. Culverts are usually overdimensioned because they are less able to cope with extraordinary large discharges and to avoid floating debris that may clog them. Whereas open channels may be bank-full or even overflow their surroundings, culverts may be washed out completely and road connections broken. Annex 10 describes methods for this overdimensioning.

Coarse debris can clog small culverts easily. Hence, they need regular inspection and cleaning. A trash-rack at the entrance can be useful in waterways that carry this type of pollution (dead vegetation, or even dead cattle in some regions). A floating beam can hold back floating vegetation. However, both require regular cleaning.

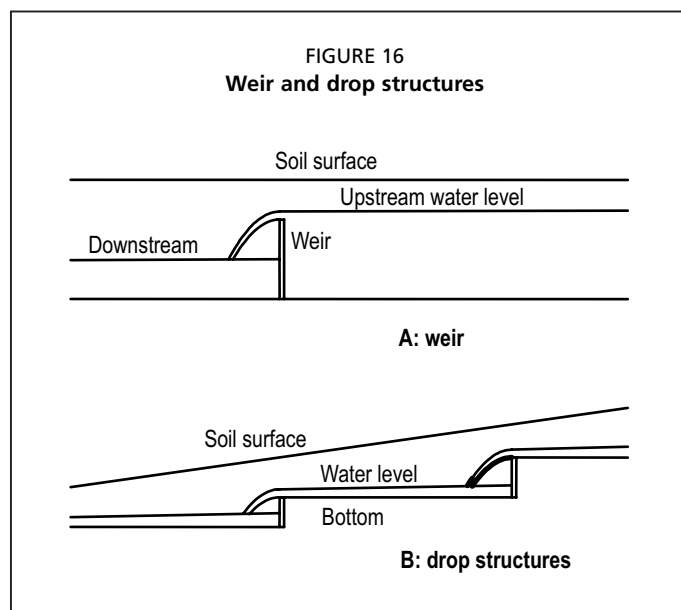
### Weirs and drop structures

Weirs are used to separate different water levels that would otherwise lead to deep excavations upstream or to an excessive flow velocity and erosion. They can be adjustable or have a fixed crest level (Figure 16). This crest can be sharp or broad, in which case a different coefficient is used for design (Equations 7 and 8 in Annex 10). There are various kinds of weir, belonging to two groups:

- Fixed weirs. These are the simplest type, but their width may not be ample enough to handle heavy discharges. In this case, “long nose” (“duck bill”) weirs may be a solution.
- Movable weirs. These are of different types varying from planks or stop logs resting in grove side-walls to self-adjusting valves acting on upstream water levels or forming part of a remotely controlled system.

Drop structures (Figure 16) are used in sloping lands where the bottom gradient must be smaller than the ground slope to prevent erosion. They are necessary to maintain the permissible flow velocity, and to dissipate the excess head. Where the energy drop exceeds 1.5 m, inclined drops or chutes should be constructed; and where it is less, straight drop structures are preferred.

Weirs and drop structures cause an improvement in water quality through aeration. The overflowing water falls into the downstream section, thereby increasing its oxygen content. As a consequence, degradable organic substances break down more rapidly.



### **Pumping stations and sluices**

The capacity of pumping stations and sluice structures is determined by the expected flow under unfavourable circumstances, i.e. a design discharge combined with high water levels outside the project. Compared with sluices, pumping stations are not much affected by outside floods, but they are less flexible. Whereas sluices increase their capacity at high internal levels, the capacity of pumps is almost fixed. Tables A11.1–11.3 show examples of a pumping station operating under extremely adverse conditions.

A pumping station is needed where the outer water level is either always or for long periods above the desired inner water level. Drainage by pumping is often only necessary in the rainy season; then a sluice or a gate is combined with the pumping station to allow discharge at low outside levels.

A pumping station consists of: an approach channel, which enables uniform flow; a sump, where drainage water collects; a suction pipe; a pump or group of pumps; and delivery pipes with outlets to the receiving waterbody. Generally, the peak flow is discharged through several pumps and the base flow through only one. However, other combinations may be used according to the circumstances. An additional standby pump is usually included for safety reasons and to enable repair of one of the other pumps without losing design capacity.

Three types of pumps are commonly used according to the drainage flow to be elevated and the lift. Where the flow is less than 200 litres/s even if the lift is high, radial pumps are recommended because they have greater flexibility in relation to flow variations. Axial pumps are most suitable for water flows of up to 1 m<sup>3</sup>/s and low lift (2–4 m). Where the outer level is almost constant, and the water transports vegetation or other debris, an Archimedes screw is appropriate. The choice of pump type also depends on local conditions such as availability, experience, maintenance possibility, and prices. These pumps are driven by diesel engines or by electricity where enough power is available on the spot. Where the electricity supply is sufficiently reliable, notably in periods when rainstorms occur, electrically driven pumps are preferable to diesel pumps because they require less attention (no fuel supply organization), maintenance and management, and they can be automated easily. The design of pumps and pumping stations is discussed in Wijdieks and Bos (1994).

Where pumping stations are essential in a drainage network, then they require competent operation and solid preventive maintenance routines. Annex 10 gives calculation methods for the dynamic head and power needed (Equations 9 and 10 in Annex 10).

For sluices (and flap gates), the tides or high outside levels may hamper the drainage discharge. In combination with the storage possibilities inside, this leads to solutions that are highly dependent on local conditions. These require special calculations, based on: numerical estimation of the storage and the levels inside; the water levels outside; and the flow through the sluice opening when the inside levels are higher. Although Annex 10 includes a formula to calculate the discharge rate (Equation 6 in Annex 10), this type of calculation will not be treated in this publication. However, firms in hydraulic engineering and hydraulic institutes often have calculation methods and programs available for such cases. Details on the design, construction and maintenance of tide sluices and gates are given in De Vries and Huyskens (1994).

### **Connection with field drainage systems**

Chapters 6 and 7 consider drainage of individual farm fields. Structures to conduct this surface and subsurface water safely into the main drainage system without causing erosion are necessary. These usually consist of rigid pipe sections for subsurface drain outlets as well as for many surface water exit points. Pipe outlets should discharge above the water level of the receiving channel in order to facilitate visual inspection and to prevent bank erosion. An alternative is protection of the bank below the pipe

outlet by chutes lined with grass, concrete or rock. For large outlets, special structures are made. Their dimensions and construction materials depend on local circumstances and on the amount of water to be discharged. Details of these auxiliary structures of subsurface drainage systems are described in FAO Irrigation and Drainage Paper No. 60 (FAO, 2005).

Attention must be given to the effect of these drainage connection structures on mechanical cleaning operations, especially where they occur at many points. In this respect, chutes and special constructions are more convenient than protruding pipes.

## DESIGN REQUIREMENTS AND CRITERIA

### Water level requirements

The capacity requirement of the main drainage outlet system is that it maintains sufficiently low water levels under unfavourable conditions. This means that in wet periods occurring with a frequency of once in 5–10 years, it must provide an adequate outlet for the field drainage systems so that these outlets still have free discharge into the main system or – if that is not always and everywhere possible – are only submerged temporarily and slightly.

The water levels are governed by the following data:

- specific discharge (drainage coefficient);
- design discharges of channels;
- hydraulic gradients and geometry of channels;
- head differences for culverts, bridges, weirs, sluices and pumps.

For the design, the channel system is divided into sections in parts that are small enough to be considered homogeneous in discharge and gradient, so that within each section the bottom width and water depth will be the same. Bridges, culverts, weirs, sluices and pumps are treated as separate structures.

### Specific discharge

Main drainage system discharges are generated by various field drainage processes. Of these, the surface drainage processes are usually the most critical.

The specific discharge is the rate at which excess water must be removed by the system without difficulty. In humid climates, it is the runoff that occurs on average from rainfall with a frequency of once in 5–10 years, increased with water from other sources (e.g. seepage). It is usually expressed in millimetres per day (to be comparable with rainfall) and is later converted into a drainage coefficient expressed in litres per second per hectare for further calculation. A less probable precipitation event is sometimes taken (once in 50–100 years) in order to check the safety of the system and the extension and duration of the flooding under extreme circumstances (yet longer times where human lives are at stake). Gumbel's method (Annex 2) may be used to predict such rare phenomena from a limited amount of data. For humid areas, there are several methods to estimate the discharge intensity for design (Chapter 6). However, the effects of climate change must be kept in mind.

Under arid conditions, not more than 1.5–2 mm/d is usually required for salt control and irrigation losses (Chapter 7). However, where rainy seasons occur (e.g. monsoons), this coefficient may be much higher.

In principle, expected seepage should be added. However, in humid areas, it is usually negligible compared with the rainfall. However, in arid regions, the drainage coefficient is low and seepage can be of comparable magnitude or even higher. Moreover, where seepage is saline, then the soil salt balance of the rootzone may be affected significantly in arid regions.

Impermeable surfaces, such as areas with bare rocks, asphalt road, buildings and horticulture under glass or plastic, have a large specific discharge. This is because infiltration in the soil is impossible. In agricultural areas, the influence of these areas

is usually of minor importance. However, built-up and covered areas tend to become more extensive over time, especially where large cities come into existence or where covered horticulture or orchards with intensive surface drainage systems become widespread. Problems may arise in periods with exceptionally intense rainfall. Where such problems occur, they may lead to a revision of the drainage system in a distant future. This involves mainly an increase in the open water storage by allowing certain low-lying areas to be flooded (wetlands, or retention basins) in critical periods as compensation for loss of soil and land surface water storage.

### Design discharges of channels

In areas with rainfall, all discharges from upstream sources must be added in order to calculate the necessary transport capacity at the end of each section below the stated highest admissible water levels as well as for any other construction belonging to the drainage system, taking into consideration the effects of retention and different travelling times in the discharging subdrainage catchments.

The design flow for return periods of 5–10 years is determined at representative places:

- at the outlet of contributing smaller channels;
- at the beginning and end of each of channel section;
- at other constructions;
- at the final outlet.

At these places and also in channel sections in between, control points are located where characteristics such as surface elevation and other data are measured.

In reality, the flow rate changes with time, and storage in the channels will cause the discharge process to be non-steady. Nevertheless, in many cases, the channel storage is relatively small in comparison with the storage in a pre-wetted soil (low percentage and some 10–20 percent, respectively). Therefore, the storage leading to non-steady effects is mainly located in the subsurface drainage system of the fields and not so much in the main system (provided most outflow is via the groundwater). Moreover, the channels are often short enough to ignore outflow retardation by travelling discharge waves, so that steady-state calculation is often a good approximation. However, in cases where surface runoff is important, the storage in the fields is much smaller and, consequently, the design discharges for the main system become far higher.

Non-steady-state calculations for runoff normally begin at the upper end of open drains and proceed downstream. Determinations on the time of the runoff peak, its shape and duration are used to calculate the size of outlet drains. Generally, the empirical method of the unit hydrograph is applied (Annex 14). In this case, the shape of each contributing area and the slope of the watersheds enter into the channel-sizing equation.

For steady-state calculations in a short channel section, the flow is taken as flow from upstream sections plus the inflow into that proper section. Both flows are calculated as the product of the specific discharge ( $q$  in litres per second per hectare) multiplied by the contributing area ( $A$  in hectares) in order to obtain the flow ( $Q$  in cubic metres per second). This gives a slight overestimation, but the difference is on the safe side.

A reduction is often applied to the upstream flow from large areas ( $Q$ ). It is in the form of an exponent  $n$  ( $< 1$ ). Where the local rainfall is patchy, the area for considering reduction is above some 1 000 ha. Where the local rainfall is widespread, reduction may be applied if the upstream area is larger than 50 000 ha. Recommended area reduction factors ( $n$ ) can be consulted in Smedema, Vlotman and Rycroft (2004).

In irrigated areas of arid regions where rainfall is negligible, the accumulation of discharges from different parts of the system is not necessary unless flooded rice is grown. In this case, a high drainage discharge capacity is required at the end of the growing season. This is because all farmers want to evacuate the remnants of the

standing water layer in a relatively short time. As not all fields are irrigated at the same time in non-rice areas, the peak discharges from the different sections do not occur at the same time. Thus, the peak discharge from the entire system is less than the accumulated peak discharges from the sections. FAO (1980) has provided values for the multiplying factors to determine the design discharge for collector drains as related to the fraction of the area that is irrigated simultaneously.

### **Exceptional discharge**

In order to check the safety of the system during discharges with return periods of 50–100 years (which may occur at any time), the calculations are sometimes repeated with a value of  $q$  of 1.5–2 times higher than the design coefficient. For such rare occasions, the water levels may become much higher than normally allowed, but disasters such as serious floods or severe damage must be avoided.

### **Hydraulic gradients and head differences**

The hydraulic gradient of a channel section is the slope of the hydraulic energy line along the channel. At low velocities ( $< 0.5$  m/s), this line is almost equal to the slope of the channel water surface. It must be more or less parallel to the slope of the land along the channel. Initially, the average hydraulic gradient available for gravity discharge can be chosen to be approximately the same as the surface gradient. Where the terrain is completely flat, it is necessary to choose a small hydraulic gradient. This must be enough to allow sufficient water flow. However, considering the need to avoid erosion, the flow velocity should not exceed 0.5 m/s. In silty soils, it may be as low as 0.20 m/s.

The bottom slope of an open-channel section should normally be equal to the average hydraulic gradient. Values of 0.05–0.1 per thousand are common in flat areas (even lower where the area is extremely flat). To create a higher gradient in these cases, discharge by pumping from one section into another could be considered. However, the capitalized operation costs may easily exceed the saving on channel dimensions.

### **Longitudinal profile**

In a longitudinal profile of a channel, the level of the strip of land along the top of the banks and the water levels to be tolerated at design discharge should be indicated, together with the location of buildings and confluences. Sudden changes in the gradients should be avoided and, where necessary, occur only at the limits of a section. Where sudden water level changes are required by the topography (to avoid deep excavations or excessive flow velocities), weirs are needed. Their location follows from land surface measurements.

Head losses caused by weirs and other structures must be shown in the channel hydraulic profiles. Weirs and culverts cause differences in head between their upstream and downstream ends, and weirs in particular lead to backwater effects that may be noticeable far upstream in flat country.



## Chapter 6

# Surface drainage

### INTRODUCTION

On flat agricultural lands, with slopes often below 0.5 percent, ponds form where the infiltration into the soil is less than the amount of water accumulated after rainfall, snowmelt, irrigation or runoff from higher adjacent places. In cold climates, a combination of snowmelt and frozen subsoil is particularly troublesome, while in dry regions so is an irrigation followed by unexpected heavy rain. Ponds form on the ground surface, especially where the infiltration rate is below the precipitation intensity. This process also occurs where the groundwater is deep.

Fine-textured soils, especially ones with a weak structure, and soils that form crusts easily are most susceptible to low infiltration and ponding. The cause is usually at or very near to the ground surface, in the form of natural pans or human-induced compacted layers such as plough soles. Deeper layers of low permeability are sometimes the cause of the formation of a perched water table.

Another cause of pond formation is insufficient subsurface drainage (natural or artificial), causing groundwater tables near or even above the surface. In this case, the flow is not restricted by insufficient infiltration into the soil but by the limited discharge of groundwater. The two processes sometimes interfere. A temporary high groundwater level may cause slaking and crust formation, which then causes stagnation of water on the surface, even after slight rains. Such pools tend to become larger during further rains.

In temperate climates with low-intensity rainfall, the precipitation rate is usually lower than the infiltration into the soil. Thus, surface runoff is limited to special cases, i.e. steep and barren slopes, very impermeable soils, land compacted by heavy machinery during the harvest of root crops, and soils that are susceptible to crust formation. In summer, the land is dry enough to absorb even a heavy shower. In such climates, subsurface discharge dominates (Chapter 7). In places where surface runoff occurs, local or temporal solutions are common (usually small ditches).

In climates where rainfall is more torrential, the volumes of surface runoff can be considerable, especially on soils with low infiltration rates and from land that has been conditioned (smoothened, beds, furrows, etc.) to reduce the incidence of ponding in high-value vegetable crops and orchards. Both rainfall intensity and infiltration rate are functions of time, and their combination leads to a critical period when conditions are worst. Such a period usually lasts a few hours. Where the type of agriculture requires its removal, as is usual in flat areas, surface drainage is needed. In addition, part of the infiltrated water must also be removed by subsurface drainage, but this flow comes later.

Surface water stagnation has negative effects on agricultural productivity because oxygen deficiency and excessive carbon dioxide levels in the rootzone hamper germination and nutrient uptake, thereby reducing or eliminating crop yields. In addition, in temperate climates, wet places have a relatively low soil temperature in spring, which delays the start of the growing season and has a negative impact on crop yields. Excess water in the top soil layer also affects its workability.

The length of the critical period of crop inundation must be determined from local experience as it varies according to climate, soils, crop tolerance, crop development stage and cropping conditions. In humid temperate regions, common field crops,

such as maize and potato, usually require designs to remove ponded rainfall from the drainage area within 24 hours. Some higher value horticultural crops may require a 6–12-hour removal time during the growing season, while other crops (e.g. sugar cane) can tolerate ponding for a couple of days.

The objective of surface drainage is to improve crop growth conditions by providing timely removal of excess water remaining at or near the ground surface before the crops are damaged. Surface drainage is also needed to guarantee soil workability and trafficability, so preventing delays in soil preparation operations and harvesting, respectively.

In order to do this effectively, the land surface should be made reasonably smooth by eliminating minor differences in elevation. It should preferably have some slope towards collection points, such as open field drains or shallow grassed waterways, from where water is discharged through outlets especially designed to prevent erosion of the ditch banks. Land smoothing is the cheapest surface drainage practice and it can be performed on an annual basis after completion of tillage operations (Ochs and Bishay, 1992).

On sloping and undulating lands, generally with natural slopes of more than 2 percent, ponding is not usually much of a problem, except for a few small depressions. However, the resulting runoff may cause severe erosion during heavy rains. Where this occurs, reshaping of the land surface into graded terraces that generally follow the contours is needed in order to promote the infiltration and the storage of useful moisture in the soil. The necessary earth movement can at the same time be used to fill the small depressions where runoff tends to collect. Earth movement is expensive (at least US\$2/m<sup>3</sup> even in low-income countries) and it requires considerable expertise and further maintenance because of soil subsidence and settling. This chapter does not address land grading and levelling aspects. Instead, reference is made to Sevenhuijsen (1994) for land grading and levelling calculations.

The field surface drains (furrows or shallow ditches) discharge into a network of open ditches or grassed waterways and larger watercourses. The main drainage system (described in Chapter 5) removes excess water to points outside the project area. Care must be taken to protect stretches where surface runoff collects and enters into field surface drains or where these drains enter larger ones. These are the points where gullies can start and where sediments enter into the main drainage system. At these transition points, provisions are needed to control erosion, even in flat lands.

In this chapter, the drainage systems required to remove safely the excess of surface water are described first. Later, methods to estimate surface drainage coefficients, which are required in order to design each component of the drainage system, are considered with technical details added in the annexes. Flat lands and sloping lands are considered separately because of their specific conditions concerning surface runoff and soil erosion control.

## **SURFACE DRAINAGE SYSTEMS FOR FLAT LANDS**

In flat lands, the approaches to cope with excess surface water depend on the circumstances. Where high groundwater is not a problem, surface systems, such as furrows and raised beds, are sufficient. However, a system of shallow ditches, combined with surface drains where necessary, is often used to cope with high groundwater as well as surface water.

### **Furrow at the downstream end of a field**

Where there is a small slope (either natural or by land grading), surface runoff from an individual field may be discharged into a furrow running parallel to the collector ditch at the downstream end of the field. Bank erosion may be prevented by a small dyke along the ditch. The water collected in the furrow is then discharged safely

into the open ditch through a short underground pipe (Figure 17).

The same drainage outlet is generally used for removing excess irrigation water, especially in rice fields.

**Ridges and furrows**

Where crops are grown on ridges with furrows in between, their somewhat higher elevation protects plants from inundation. The furrows also serve as conduits for the flow of excess water, which is collected by an additional furrow at the downstream sides of the field and discharged into the ditch in a similar way as described above.

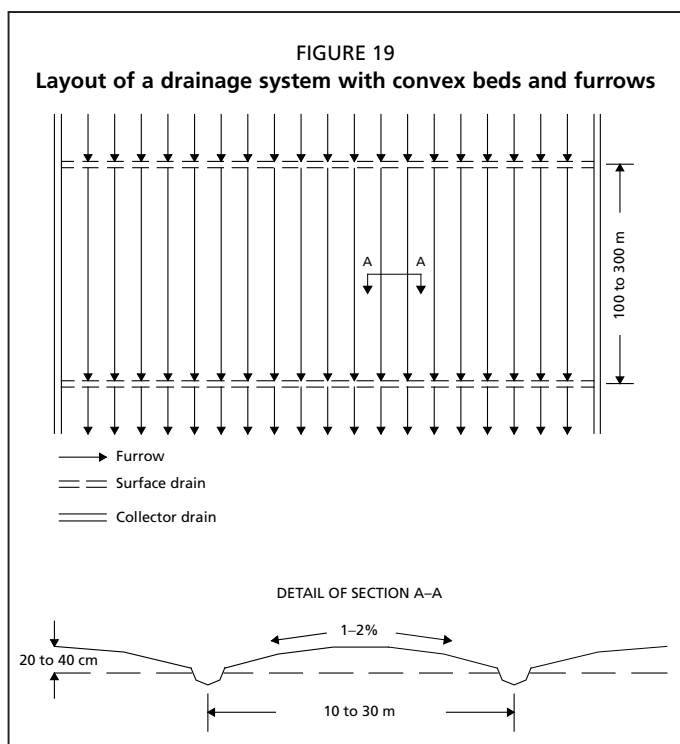
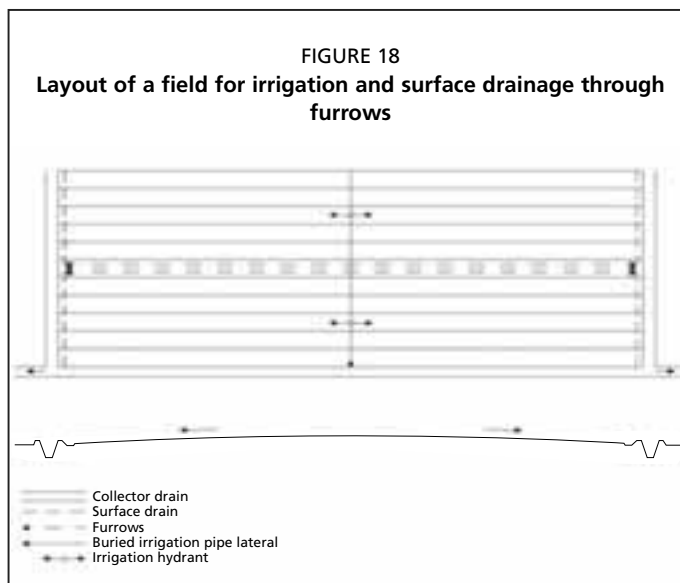
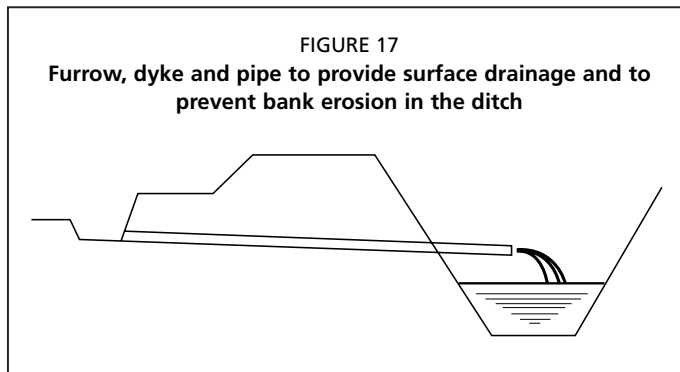
The ridged fields may have a small slope towards the sides. Where fields are made highest in the middle (e.g. by land grading), this position can also be used for irrigation supply to the furrow (Figure 18).

The length and slope of the furrows depend on the field dimensions and the soil conditions. The length usually ranges from 150 to 250 m. The slope along their length is usually some 0.5–5 per thousand. This guarantees a flow velocity of less than 0.5 m/s, low enough to prevent erosion on most soils.

**Convex raised beds and furrows**

In flat lands with low infiltration rates, surface runoff is facilitated by shaping the land into raised beds with a convex form between two furrows. Beds run in the direction of the prevailing slope, as shown in Figure 19.

A rather low lateral direction slope of these beds (1–2 percent) is sufficient. In some soils, beds that are too high may become subject to erosion. Raised beds can be made on-farm by repeated directional ploughing or by land grading. The intervening furrows are shallow enough to be passable for agricultural implements and cattle. These furrows should have a



slight longitudinal slope for their discharge, either directly to the collector ditch, as in grassland where the soil is sufficiently protected, or to a system with a downstream furrow acting as a surface drain (described above).

While normal ploughing operations must always be carried out in the same way the beds were ploughed originally, all other farming operations can be carried out in either direction.

The beds have a length of about 100–300 m. The bed widths and their slopes depend on soil permeability, land use and farm equipment. Some recommendations, according to Raadsma and Schulze (1974) and Ochs and Bishay (1992), are:

- 8–12 m for land with very slow internal drainage ( $K = 0.05$  m/d);
- 15–17 m for land with slow internal drainage ( $K = 0.05$ – $0.10$  m/d);
- 20–30 m for land with fair internal drainage ( $K = 0.1$ – $0.2$  m/d).

The elevation of the beds, i.e. the distance between the bottom of a furrow and the top of the bed, can range from about 20 cm for cropland up to 40 cm for grassland, where land covering reduces erosion hazard. The furrows between the beds are normally about 25 cm deep with gradients of at least 0.1 percent.

The bedding system does not provide satisfactory surface drainage where crops are grown on ridges, as these prevent overland flow to the furrows. Bedding for drainage is recommended for pasture, hay or any crop that allows the surface of the beds to be smoothed. It is less expensive but not as effective as a parallel furrow drainage system. The system cannot be combined with surface irrigation, although sprinkler and drip irrigation remain possible.

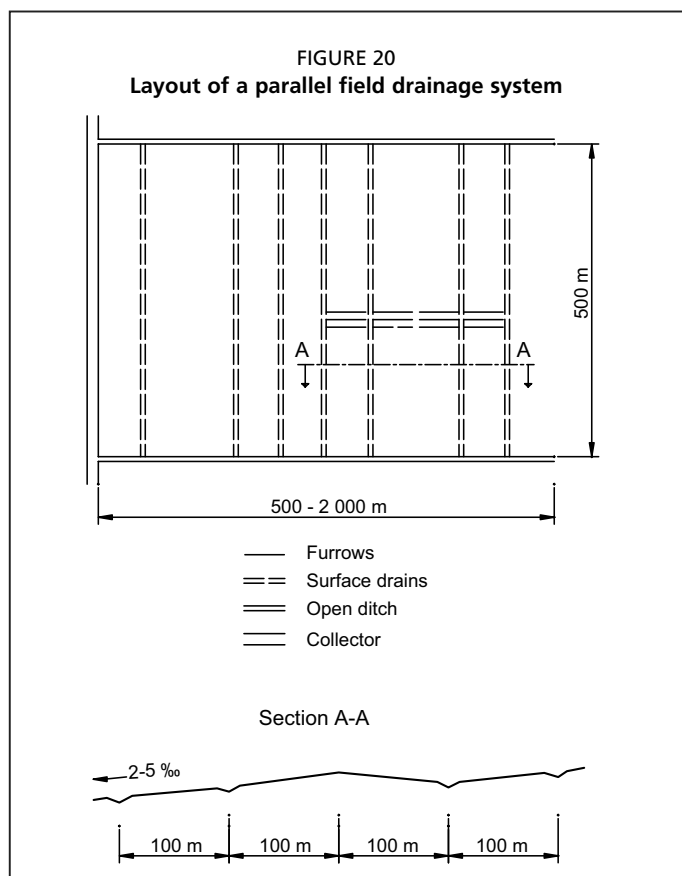
### Parallel surface drains at wide spacings

Parallel field drainage systems are the most common and generally the most effective design recommended for surface drainage of flat lands, particularly where field surface

gradients are present or constructed. Parallel field drainage systems facilitate mechanized farming operations.

Shallow field drains are generally parallel but not necessarily equidistant, and spacing can be adjusted to fit farm equipment. The spacing of parallel field drains depends on the crops to be grown, soil texture and permeability, topography and the land slope. Drain spacing generally ranges from 100 to 200 m on relatively flat land, and it depends on whether the land slopes in one direction or in both directions after grading (Ochs and Bishay, 1992). Parallel field drains should usually have side slopes not steeper than 1:8 (if equipment will be crossing) and longitudinal grades ranging from 0.1 to 0.3 percent (never less than 0.05 percent). Figure 20 shows some of the details for a typical parallel field drainage system.

To enable good surface drainage, crop rows should be planted in a



direction that will permit smooth and continuous surface water flow to the field drains. Ploughing is carried out parallel to the drains, and all other operations are perpendicular to the drains. The rows lead directly into the drains, and should have a slope of 0.1–0.2 percent. Where soil erosion is not probable, the row slope may be as high as 0.5 percent.

Under some conditions, deeper field drains are also used to provide subsurface drainage. In several places, especially at the outlets, small filled sections with culverts are often needed to provide access to the fields.

### Parallel small ditches

This system employs small ditches 0.6–1.0 m deep. It is used with the dual purpose of removing surface runoff and controlling high water tables. The system is especially useful where the groundwater stagnates on a poorly permeable layer at shallow depth (perched water tables), but also functions to prevent a high rise of the real groundwater during wet periods. In this case, all farming operations are carried out parallel to the drains.

The distance between the small ditches is usually 50–100 m, with a length up to 500 m (Figure 21).

With wider spacings or low-permeability soils, additional shallower ditches can be used instead of the furrows shown in Figure 21. The length of these ditches depends on the spacing of the ditches receiving the discharge. Longitudinal slopes of 2–5 per thousand are recommended in order to secure their discharge and, at the same time, to prevent their erosion. Where surface runoff is a problem, shaping the land will provide either one- or two-sided discharge to these ditches.

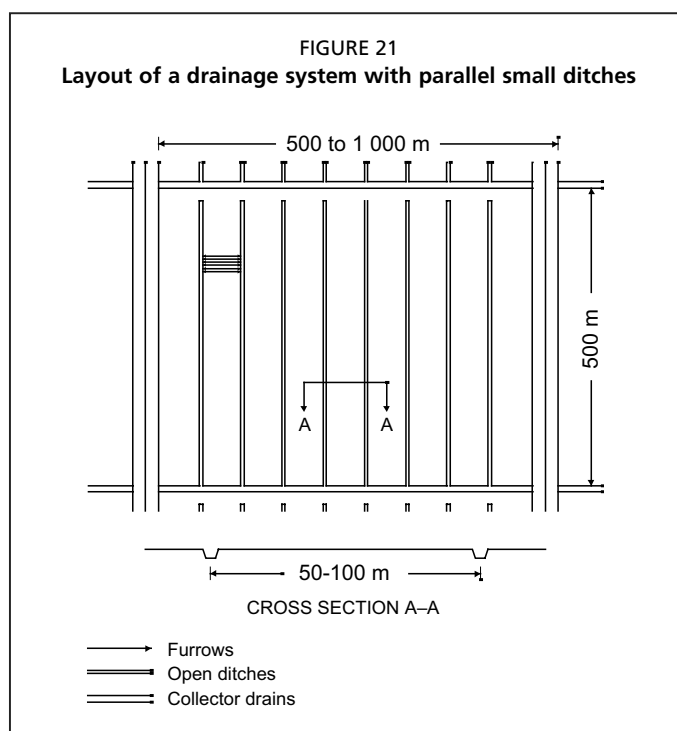
Erosion protection for parallel ditches is sometimes needed, especially on arable land. The system in Figure 17, with a small parallel furrow that discharges at its lowest points through pipes into field collector ditches, can be used for this purpose. In pastures, the side slopes of the ditches are usually covered with vegetation, and protection against surface runoff is seldom needed.

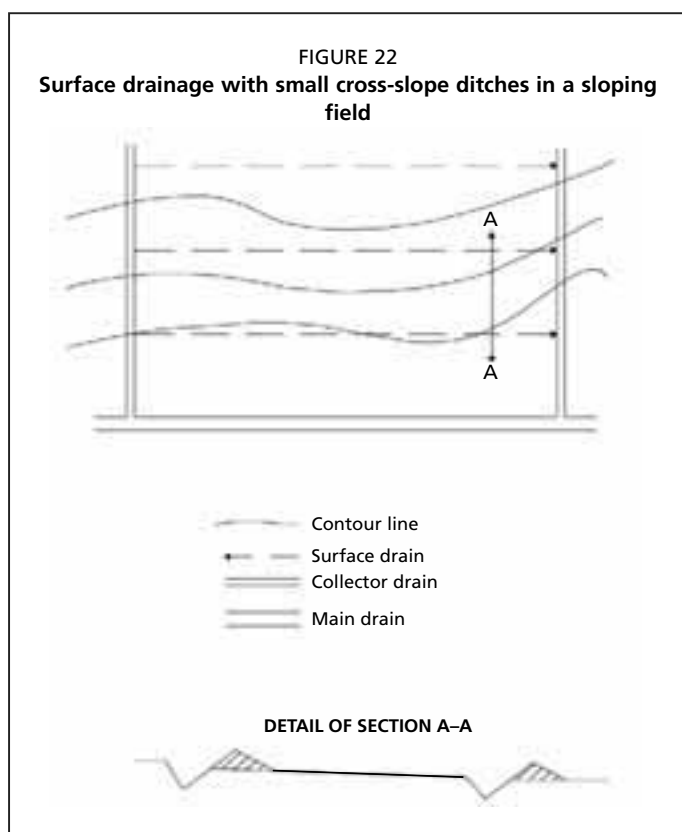
### SYSTEMS FOR SLOPING AND UNDULATING LANDS

With undulating and sloping lands, there is ample opportunity for free surface runoff, and often also for natural underground drainage to a deep water table. However, erosion of such lands often causes sedimentation elsewhere, while the runoff leads to inundations in the lowest parts of the area. Groundwater flow may cause seepage in lower places.

### Cross-slope drain systems

Where surface runoff threatens agricultural fields in sloping lands, small cross-slope ditches can be made at their lower end, running almost along contours. Ditch spacings depend on factors such as gradient, rainfall, infiltration into the soil, hydraulic





conductivity, erosion risk and agricultural practices. No general rules can be given. Surface runoff is discharged into open collector ditches running in the direction of the natural slope to discharge into a main waterway (Figure 22).

The open collector ditches should not erode. Therefore, the slope of the land should be not more than a few percent; otherwise, the collector ditches must be provided with weirs or drop structures.

To facilitate agricultural operations, the ditches can be made passable for machinery or (where this is not desired) provided at their ends with a dam and an underground pipe leading to the collector drain. The width of the dam and the length of pipe depend on the type of machines to be used, but a pipe length of about 5 m is sufficient. When constructed, the excavated materials should be used in low areas and on the downhill side of the ditches.

### Random field drainage systems

Random drains are applicable where fields have scattered isolated depressions that cannot be easily filled or graded using landforming practices. The system involves connecting one depression to another with field drains, and conveying the collected drainage waters to suitable outlets. Drain depths should be at least 0.25 m, with dimensions depending on the topography of the area and on discharge design, considering the contributing area. This minimum depth is usually applied in the uppermost depression areas. To permit crossing by farm machinery the side slopes should be no steeper than 1:8. The spoil or excavated material from random field drains should be used to fill small depressions or be spread uniformly so that it does not interfere with surface water flows. Smoothing is sometimes required in order to improve the effectiveness of the surface drainage in some of the flatter parts of these fields (Ochs and Bishay, 1992).

### Surface drainage in undulating lands

On undulating lands, the layout of an improved drainage system must follow as much as possible the natural topography of the existing watercourses (Figure 23). In narrow valleys, one open drain is usually sufficient, but wider plains may require interceptor or diversion drains, often in addition to contour embankments at the foot of the surrounding hills, to protect areas from flooding caused by surface runoff from higher lying adjacent lands.

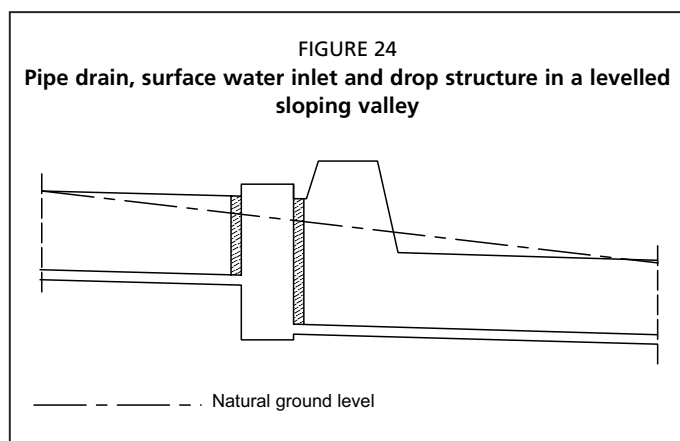
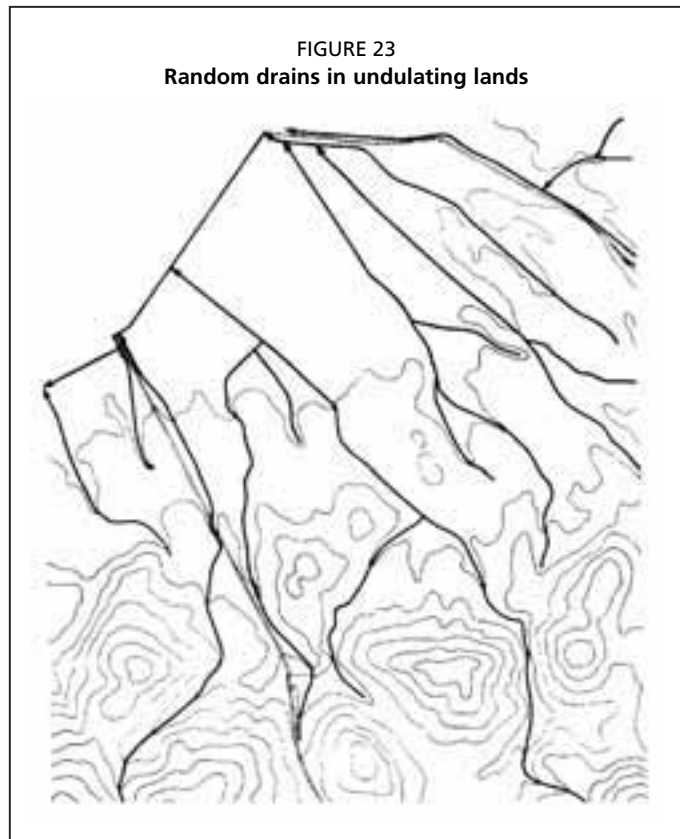
A surface drainage system as shown in Figure 23 not only captures runoff from the higher grounds, but it can also intercept groundwater flow. Infiltrated water can reappear in the valley as seepage, causing a more permanent type of waterlogging, and in dry climates severe salinization. This situation is common near the foot of hills bordering flat valleys, and also in low-lying lands that receive tail-end water and/or

seepage water from adjacent higher lying irrigated areas.

The type of interceptor drains used depends on the relative amounts of runoff and seepage. The former usually dominates, in which case open ditches are needed. Their side slopes, especially the upstream one, must be very flat in order to prevent erosion, and grassed waterways are often useful. A grassed filter strip is also recommended for the upslope side of the interceptor ditch. It catches sediments carried by the water and prevents erosion of the slope.

Where seepage is of importance, deeper ditches are required, and pipe drains can be used if there is little or no surface runoff. Drainage for intercepting subsurface flow is described in Chapter 7 (with more detail in Annex 21).

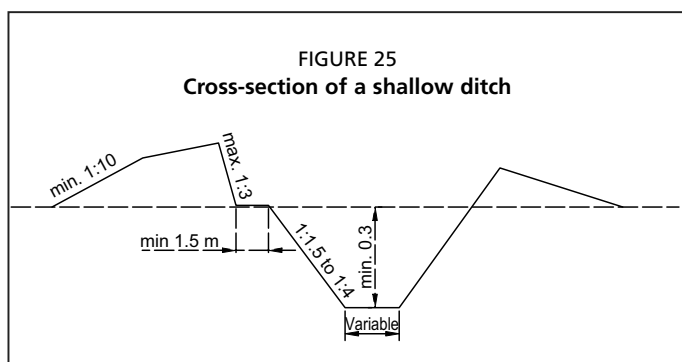
Some narrow valleys still have a considerable longitudinal slope, the open ditch being liable to erosion. By grading the land, the valley may be divided into compartments separated by small transverse dams. An open drain situated near the centre of the valley collects water from upstream and transports it to the lower end of each compartment. There, a weir or drop structure leads to the next one. In some cases, pipes can be used in combination with inlets of surface water situated at the downhill end of the compartment. Such inlets can be made from large-diameter plastic pipes surrounded with gravel (Figure 24).



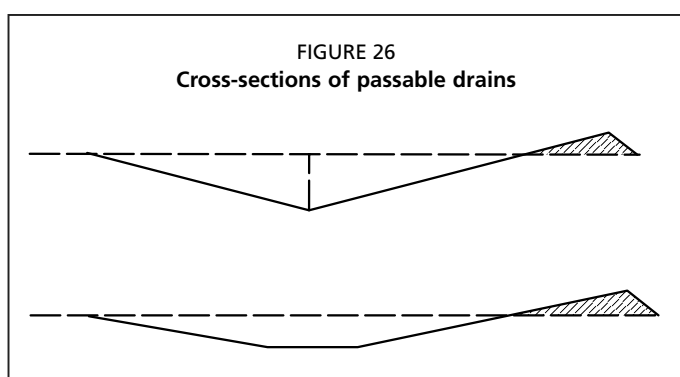
### CROSS-SECTIONS OF SURFACE DRAINS

Ditches must have enough capacity to transport the drainage water in wet periods. However, they are sometimes made wider than needed in order to create more storage in the open water system. Such temporary storage is a good way of diminishing the peak outflows from the area, as occurs after heavy rains. Thus, it reduces the required capacity of downstream constructions, such as the larger watercourses, culverts, and pumping stations.

The cross-sections of ditches are usually trapezoidal (Figure 25) although small ones may be V-shaped. Their dimensions vary according to: the expected runoff, the necessity for open water storage, the capacity to be passable for machinery, the risks of bank erosion, and the available means for maintenance.



Source: Adapted from Raadsma and Schulze, 1974



**TABLE 5**  
**Recommended dimensions of trenches and open ditches**

Type of drain	Depth (m)	Bed width (m)	Side slope (v:h)	Maximum side slope (v:h)
Furrows	0.20–0.30	-	-	-
Passable drains, V-shaped	0.15–0.30	-	1:10	-
Passable drains, trapezoidal	0.25–0.50	2.0–2.5	1:10	1:8
Ditches, V-shaped	0.30–0.60	-	1:6	1:3
Ditches, V-shaped	> 0.60	-	1:4	1:3
Ditches, trapezoidal	0.30–1.0	As required	1:4	1:2
Ditches, trapezoidal	> 1.0	As required	1:1.5	1:1

Because ditches tend to hamper agricultural operations, passable drains are often used (Figure 26), designed with respect to agricultural land use rather than on hydraulic properties. Where they tend to erode, they are sown with grasses (grassed waterways). However, grassed waterways are not always a solution because sometimes the grass does not grow or it does not survive the dry season.

As a guide, Table 5 gives some values recommended by the International Institute for Land Reclamation and Improvement (ILRI) (Raadsma and Schulze, 1974; Sevenhuijsen, 1994) and others for small ditches and surface drains.

Ridges and furrows are made by ploughing with ridge-forming agricultural machinery, passable ditches usually by grader, and steeper ones may be constructed by a special plough that shapes the required profile in one pass. Larger ditches are usually made using a backhoe. Details on machinery for construction of surface drains are given in Vázquez Guzmán (1999).

## DESIGN DISCHARGES

The discharge of excess surface water to be expected determines not only the dimensions of the structures described in the previous sections, but also those of drainage elements of the main system further downstream (Chapter 5). Peak discharges are caused almost exclusively by rainfall or snowmelt; in rare cases, they stem from irrigation losses. First, the

drainage coefficient, defined as the rate of water removal per unit of area, is estimated. Then, the flow rate, which varies with the size of the area, is calculated.

In flat lands, design discharges depend on the amount of excess rainfall to be removed by the surface drainage system during the critical period. The first item can be estimated from the water balance or through empirical formulae.

In sloping land, although surface stagnation is generally not the problem, design discharges are needed to dimension the different components of the main drainage system. Discharges stem from overland runoff processes in the basin considered. There are several methods to obtain the hydrograph of the basin (from this the design discharge can be estimated); some of them are quite sophisticated. Therefore, before describing some of the methods for calculating design discharges in flat and sloping



areas, the following section considers some principles on surface runoff.

### Basic concepts concerning overland runoff

#### Water balance

The amount of excess rainfall to be drained superficially during a critical period can be estimated from the water balance at the ground surface (Figure 27):

$$S_r = P - E - I_{nf} \quad (1)$$

where:

$E$  = direct evaporation (mm);

$I_{nf}$  = infiltration into the soil (mm);

$P$  = total precipitation (mm);

$S_r$  = excess of water at the soil surface (mm).

The excess of surface water is generally drained freely in sloping lands, but commonly through surface drainage systems in flat lands ( $D_s$ ). Part of the infiltrated water sometimes interflows through the topsoil ( $D_i$ ), but most replenishes the unsaturated zone and percolates, recharging the groundwater table ( $R$ ). Where natural drainage is not sufficient, subsurface drainage ( $D_i$ ) is required (Figure 27).

The evaporation in a period of a few hours is usually small and negligible compared with the other terms of the water balance.

The amount of rain to be expected with a given frequency in a critical period can be estimated from meteorological data. For extreme values, Gumbel's method may be used to obtain such forecasts (Annex 2 for the method, and Annex 23 for the computer program).

Generally, only rainfall data for 24 hours are available. However, the length of critical periods can be 6–12 hours and, moreover, heavy rainfalls usually occur in this time interval. Nevertheless, estimations for these short periods can be made, for example with the following coefficients (Smedema, Vlotman and Rycroft, 2004):

$$P_6 / P_{24} = 0.5-0.7 \quad (2)$$

$$P_{12} / P_{24} = 0.6-0.8 \quad (3)$$

where:

$P_6$  = estimation of the amount of rainfall in 6 hours (mm);

$P_{12}$  = estimation of the amount of rainfall in 12 hours (mm);

$P_{24}$  = amount of precipitation in 24 hours (mm).

The distribution of the amount of rainfall accumulated in 6 hours can be estimated with the coefficients shown in Table 6.

Where only rainfall data for one-year return period are available, estimations for 5 and 10 years can also be made with the following coefficients (Smedema, Vlotman and Rycroft, 2004):

$$P_{T5} / P_{T1} = 1.5-2.0 \quad (4)$$

$$P_{T10} / P_{T1} = 1.7-2.5 \quad (5)$$

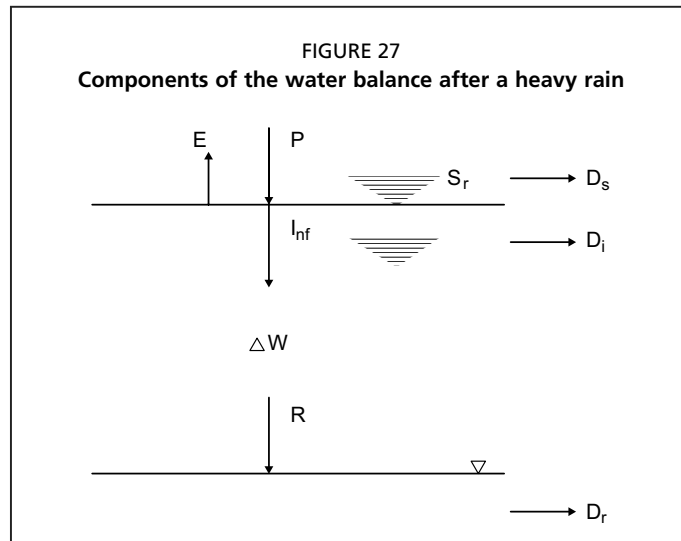
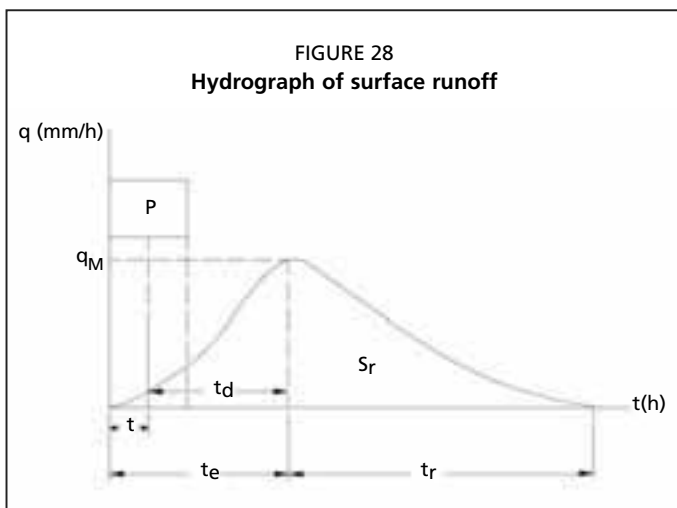


TABLE 6  
Model of distribution of the amount of rainfall accumulated in 6 hours

t (h)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
%	0	2	8	15	22	60	70	78	84	88	92	96	100

Source: WMO, 1974.



where:

$P_{T1}$  = precipitation for 1-year return period (mm);

$P_{T5}$  = precipitation for 5-year return period (mm);

$P_{T10}$  = precipitation for 10-year return period (mm).

For snowmelt combined with a still frozen soil, it should be expected that the total precipitation accumulated as snow during the foregoing frost period (minus some evaporation by sublimation) will become runoff within a few days.

More important to a water balance is the infiltration, which depends greatly on the soil properties. While

coarse sands will take almost any rainfall intensity, finer sands (e.g. wind-blown dunes) can show surface runoff during heavy showers. Silt loams have a tendency to form crusts, and some clay soils have a low infiltration rate whereas other well-structured ones may remain very permeable.

However, all soils show an infiltration rate that varies with time. When still dry at the surface, they have a much higher intake rate than after wetting. The main reason is that at the beginning the hydraulic gradient between the wet top and the dry subsoil is very large. Eventually, the intake rate becomes constant because the soil is ultimately saturated and the hydraulic gradient has become unity owing to the effect of gravity only. Another cause of reduced infiltration is that clay swells on wetting. The determination of infiltration forms the main difficulty, but field methods are available (Chapter 4).

#### Hydrographs of surface runoff

In an agricultural area, surface runoff depends on some physical characteristics of the basin, such as its form and size, soil conditions, land slope, natural vegetation and land use. The peak flow of drainage water also depends on the characteristics of the main drainage system, such as drain density, cross-sections and gradients of the watercourses, as well as their maintenance conditions (which may restrict their water transport capacity).

After a certain amount of precipitation ( $P$ ), the specific discharge of surface drainage water at the outlet of the basin ( $q$ ) increases progressively during the elevation time or time to peak ( $t_e$ ). Once the maximum value ( $q_M$ ) is reached, the specific discharge decreases progressively during the recession time ( $t_r$ ). The time interval between the average time of the storm ( $t$ ) and the time when maximum discharge occurs is called the lag time ( $t_d$ ). These concepts are represented by their corresponding symbols in Figure 28, where the total amount of surface runoff ( $S_r$ ) can also be determined. The hydrograph for total drainage discharge can be obtained by superimposing the groundwater hydrograph on this hydrograph.

In a basin, the values of the times described above are constants as they depend on the concentration time ( $t_c$ ). This is the time interval since the beginning of the storm and the moment when runoff coming from the most distant point from the outlet of the basin contributes to the water flow at the outlet. For basins of less than 1 500 ha, the concentration time can be considered equal to the time to peak (Boonstra, 1994). If the duration of the storm is less than the  $t_c$ , only part of the basin contributes to the peak flow at the outlet; if the  $t_c$  is higher, the whole area contributes, but generally the rainfall intensity decreases with time. The  $t_c$  value depends on the flow velocity and on the length of each section of the main drainage system:

$$t_c = \sum_{i=1}^n \frac{l_i}{v_i} \quad (6)$$

where:

$t_c$  = concentration time (s);

$l_i$  = length of section  $i$  of the main drainage system (m);

$v_i$  = average flow velocity in section  $i$  (m/s).

Where the drain hydraulic cross-section, the slope and the Manning coefficient are known, the flow velocity in the watercourses can be calculated with the Manning formula. The flow velocity on the ground surface depends on the covering (land use) and slope. Figure 29 shows indicative values.

However, in agricultural areas of less than 50 ha, the concentration time can be estimated with the empirical formula developed by Kirpich:

$$t_c = \frac{K^{0.770}}{3080} \quad (7)$$

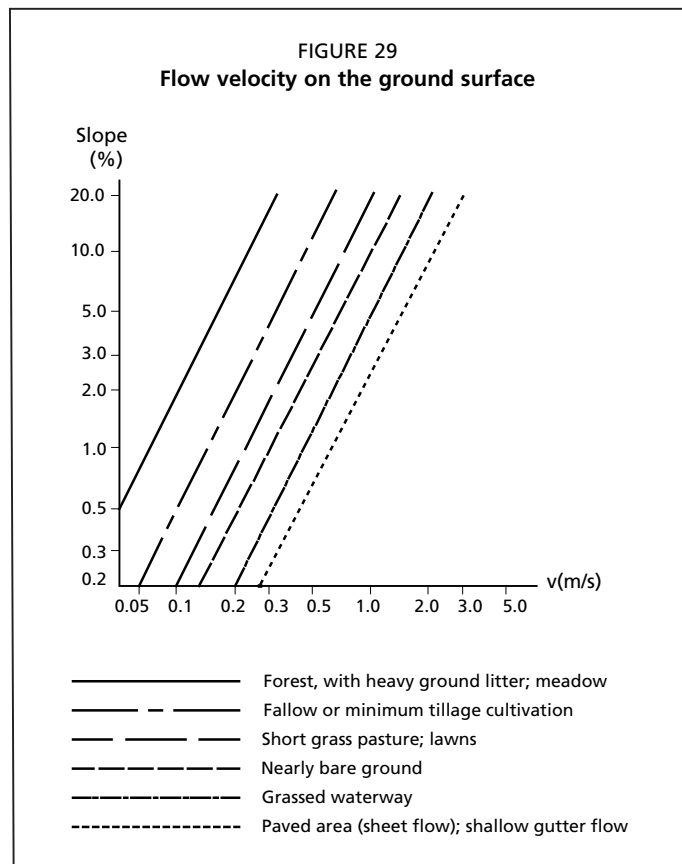
where:

$h$  = difference in elevation between the most distant point in the basin and the outlet (m);

$l$  = maximum distance between the above two extreme points (m);

$s = h/l$  = gradient;

$K \frac{l}{\sqrt{s}}$  = basin constant (m).



### Methods to determine design discharges

Different methods have been developed to determine peak water flows and design discharges. The approaches differ from sloping lands, where surface runoff is free, to flat lands. In addition to this distinction, the selection of the appropriate method for a specific project area depends on data availability.

A brief description of each method and the information required to apply it is provided below. Annexes 11–16 provide technical details and application examples. Additional information can be consulted in the literature references, especially in Boonstra (1994) and Smedema, Vlotman and Rycroft (2004).

#### *The batch method for flat lands*

For humid flat lands, a simple and approximate method, called the batch method, is based on rainfall, outflow, and storage in different reservoirs, this being:

- soil storage;
- storage in channels and ponds;
- storage by field inundations.

In the batch method, a water balance is set up in order to obtain an approximation of the consequences of different drainage coefficients on crop growth during the critical period. This method can be used to check the effectiveness of existing drainage systems, as shown in an example in Annex 11, or to select the most appropriate specific discharge for designing new drainage systems.

#### *Empirical formulae for flat areas*

In flat areas, empirical formulae can also be used. Special formulae are available for specific regions and their use is recommended if they are based on sufficient experience. As an example, the Cypress Creek formula, developed for flat lands in the east of the United States of America, is given in Annex 12. As actual conditions may differ in a project area, this formula can only be used as a first approximation to be verified later.

#### *Statistical analysis of measured flows*

The maximum discharge at the outlet of the main drainage system can be determined statistically where a data series of measured flows is available covering a period of at least 15–20 years in an area where the hydrological conditions and the land use have not changed during the historical period considered. Annex 13 shows an example of statistical analysis of measured flows.

#### *Unit hydrograph*

In agricultural areas, long data series of measured flows are rarely available to determine statistically the design discharge. However, in basins of 10 000–50 000 ha, where it is possible to assume that 2–6-hour storms are covering the area uniformly, flows have sometimes been measured for different duration rainfalls. Therefore, some hydrographs are available. By using these hydrographs, a precipitation/surface runoff relationship can be obtained. This can be used to predict the surface runoff for other series of rainfall data. The unit hydrograph developed by Sherman is based on this principle. Annex 14 provides details on this method.

#### *Rational formula*

In agricultural areas of 100–200 ha, surface runoff is produced just after precipitation where the storage capacity of water in the soil is low. No unit hydrographs are usually available, but there are sometimes some gauge points in the main drainage system. In this case, with water flow data and the characteristics of the section affected by the measurement of the water flow (surface area and hydrological conditions), a relationship can be established between the amount of surface runoff and rainfall. This relationship can be applied to other areas with similar characteristics to the reference section. The rational formula, which is based on the above principle, is described with an example in Annex 15.

### Curve Number method

In agricultural areas, the most frequent case is to have rainfall data available but no surface runoff information. In this case, surface runoff can be estimated with the available rainfall data and information on the physical characteristics of the basin concerning the rainfall/runoff relationship, by using a method based on this relationship. A method widely applied is the Curve Number (CN) method. This method was developed by the Soil Conservation Service (SCS) after studies and investigations made in basins with surface area below 800 ha.

To apply the CN method three phases are followed:

1. The amount of surface runoff expected after the design rainfall is estimated, by considering the physical characteristics of the basin.
2. The distribution of the estimated runoff during the storm period is determined by using an undimensional hydrograph.

TABLE 7  
Summary guidelines for the selection of method to determine design discharges

Type of lands <sup>1</sup>	Aim	Drainage flow conditions	Drainage basin area (ha)	Available data	Recommended method	Remarks
Flat (slope < 0.2%)	To discharge excess surface water in a critical period	Field and canal storage are relevant; overland flow, interflow and subsurface flow	Up to some thousand	Data series of measured flows (m <sup>3</sup> /s) (at least 15–20 years)	Statistical analysis of flows	Most reliable method but information not commonly available; need to check land-use changes.
			Up to some thousand	Rainfall distribution (days or hours) Evaporation (mm/d) Soil storage (mm/d) Storage in channels and ponds (mm/d) Maximum time of ponding (days or hours)	Batch method	Suitable to check performance of existing drainage facilities or to determine the design discharge
			< 5 000	24-hour excess rainfall (mm) Area served by the drain (km <sup>2</sup> )	Cypress Creek formula	To be used only as a first approximation as this formula was developed for flat lands in the east of the United States of America
Sloping (slope > 0.5 %)	To discharge peak runoff	Free overland flow	Up to some thousand	Data series of measured flows (m <sup>3</sup> /s) (at least 15–20 years)	Statistical analysis of flows	Most reliable method but information not commonly available; need to check land-use changes.
			Up to some thousand	Series of rainfall (mm) Some measured flows for 2–6 hours rainfall Unit hydrographs for 10 mm rainfall	Unit hydrograph	Method based on precipitation/surface runoff relationships not always available
			100–200	Rainfall intensity (mm/h) Area of the basin (ha) Slope (%) Soil infiltrability	Rational formula	To be used only as a first approximation as indicative values developed in the United States of America to determine the surface runoff coefficient are used
			Up to some thousand	24-hour rainfall (mm) In each land mapping unit (ha): natural vegetation and land use; agricultural practices; hydrological soil conditions associated to vegetation density; soil infiltrability; and soil moisture content previous to the design storm	Curve Number	To be used only as a first approximation as the original CN numbers were determined in the United States of America and the specific discharge is based on the SCS unit hydrograph

<sup>1</sup> For lands with slope between 0.2 and 0.5%, other factors (rainfall intensity, soil type, vegetation cover, cultivation methods, etc.) should be considered to classify the land as flat or sloping (Smedema, Vlotman and Rycroft, 2004).

3. The maximum value of the specific discharge is determined in the hydrograph obtained for the total discharge. Then, with the surface area value, the peak flow at the outlet of the main watercourse draining the basin is calculated.

Details of the CN method and an example are included in Annex 16.

This method has a wider scope of application than the rational method as it can be applied in basins with a surface area of several thousand hectares. However, the result obtained can only be considered an estimation of the peak flow. This must be further checked with measured flows in gauge stations in similar locations to the place of application (as original curve numbers were developed in the United States of America).

Table 7 provides summary guidelines for the selection of the appropriate method for determining design discharges of surface drainage according to the data available in one specific project area.

## Chapter 7

# Subsurface drainage

### INTRODUCTION

In flat lands, subsurface drainage systems are installed to control the general groundwater level in order to achieve water table levels and salt balances favourable for crop growth. Subsurface drainage may be achieved by means of a system of parallel drains or by pumping water from wells. The first method is usually known as horizontal subsurface drainage although the drains are generally laid with some slope. The second is called vertical drainage.

A system of parallel drains sometimes consists of deep open trenches. However, more often, the field drains are buried perforated pipes and, in some cases, subsurface collector drains for further transport of the drain effluent to open water are also buried pipes. The drainage water is further conveyed through the main drains towards the drainage outlet. Less common are vertical drainage systems consisting of pumped wells that penetrate into an underlying aquifer.

In sloping lands, the aim of subsurface drainage is usually to intercept seepage flows from higher places where this is easier than correcting the excess water problem at the places where waterlogging occurs from shallow seepage.

### LAYOUT OF SINGULAR AND COMPOSITE DRAINAGE SYSTEMS

There are several options for the layout of systems of parallel drains:

- singular drainage systems consisting of deep open trenches flowing directly into open outlet drains of the main system;
- singular drainage systems consisting of perforated pipe field drains (laterals) flowing directly into open drains of the main outlet system;
- composite drainage systems in which perforated pipes are used as laterals and closed or sometimes perforated pipes as collector drains. The latter discharge into the main drain outlet system.

As open trenches hamper agricultural operations and take up valuable land, field drainage systems with buried perforated pipes are usually preferred.

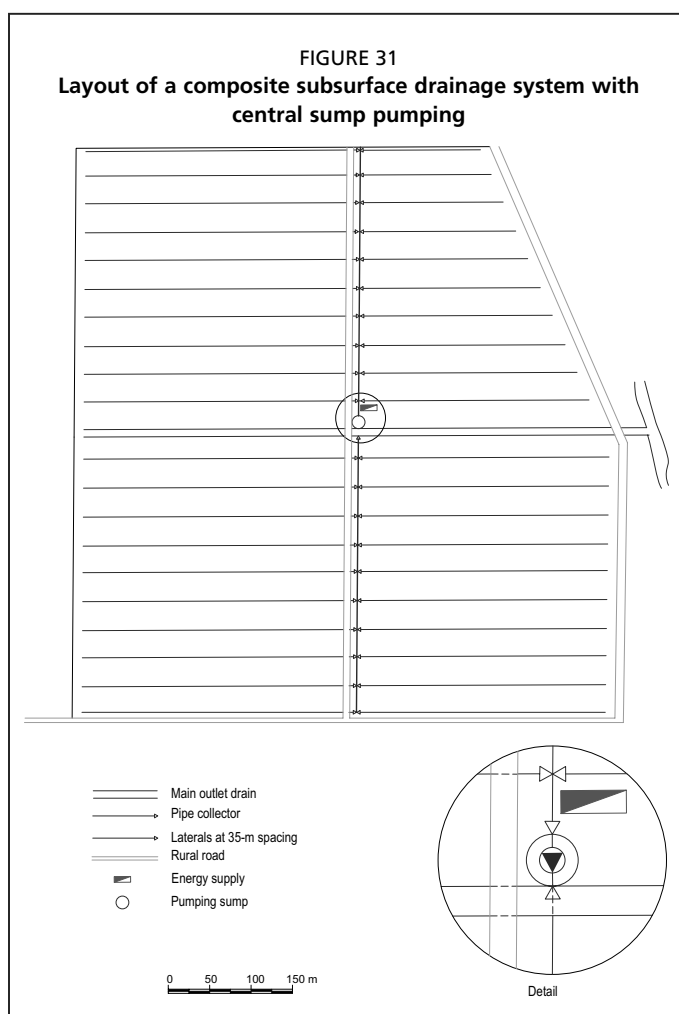
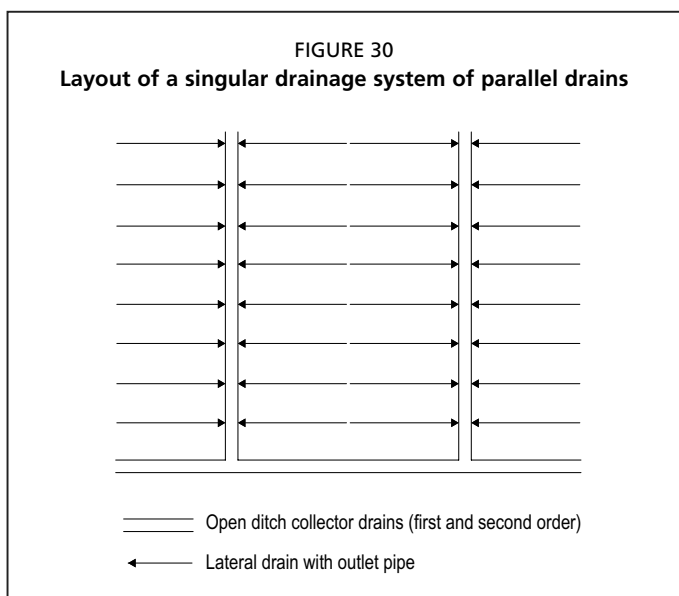
Several factors must be considered in order to select the appropriate drainage system (Martínez Beltrán, 1999), such as:

- the need to discharge surface runoff;
- the slope of the land to be drained;
- the depth of the lateral outlets;
- the maintenance requirements and possibilities;
- the design depth of the water table.

Singular subsurface drainage systems, with pipe laterals only, are appropriate:

- where, in addition to the subsurface flow, it is necessary to discharge excess rainfall through a shallow surface drainage system;
- where a certain amount of water must be stored in the open drains in order to reduce the peak flow in the outlet system;
- in very flat lands where the drainage flow is high and the available slope is low.

As an example of a singular subsurface system, Figure 30 shows the layout of the system installed in the Lower Guadalquivir Irrigation Scheme, Spain. Field drains are laid at 10-m spacing and open collector drains at 500-m spacing.



Composite subsurface drainage systems, with pipe lateral and collector drains, are generally recommended in the irrigated lands of arid regions because:

- The depth of field drains is usually greater than in the temperate zones and, consequently, large excavations would be required if open ditches were used as field or collector drains.
- The excess rainfall is generally negligible; as a consequence, drainage rates are low (although often very salty) and thus the discharge of a considerable number of parallel pipe drains can readily be collected and transported by a subsurface collector system.
- Weed proliferation increases the maintenance costs of open ditches.

This type of system is common in the Nile Delta, Egypt, where subsurface drainage systems discharge only the necessary leaching to control soil salinity and keep the groundwater level sufficiently deep to prevent salinization caused by capillary rise of saline groundwater.

Composite systems are also recommended in: sloping areas where soil erosion must be controlled and/or drainage problems are mainly manifest in patches or in topographic lows; in areas where the land is very valuable; and in the case of unstable subsoils that cause unstable banks of open drains.

In some areas, especially where the maintenance or availability of deep open drains is difficult, groups of pipe collector drains discharge into tanks (sumps), from where the water is pumped into a shallow main outlet system (where the external water level is above the field groundwater level). This is the case for arable crops and mango orchards in some parts of the Lower Indus Plain, Pakistan, and in some areas of the Ebro Delta, Spain, where horticultural crops are

grown. In the latter case, subsurface drainage systems, as in Figure 31, have been installed to control the saline groundwater table.

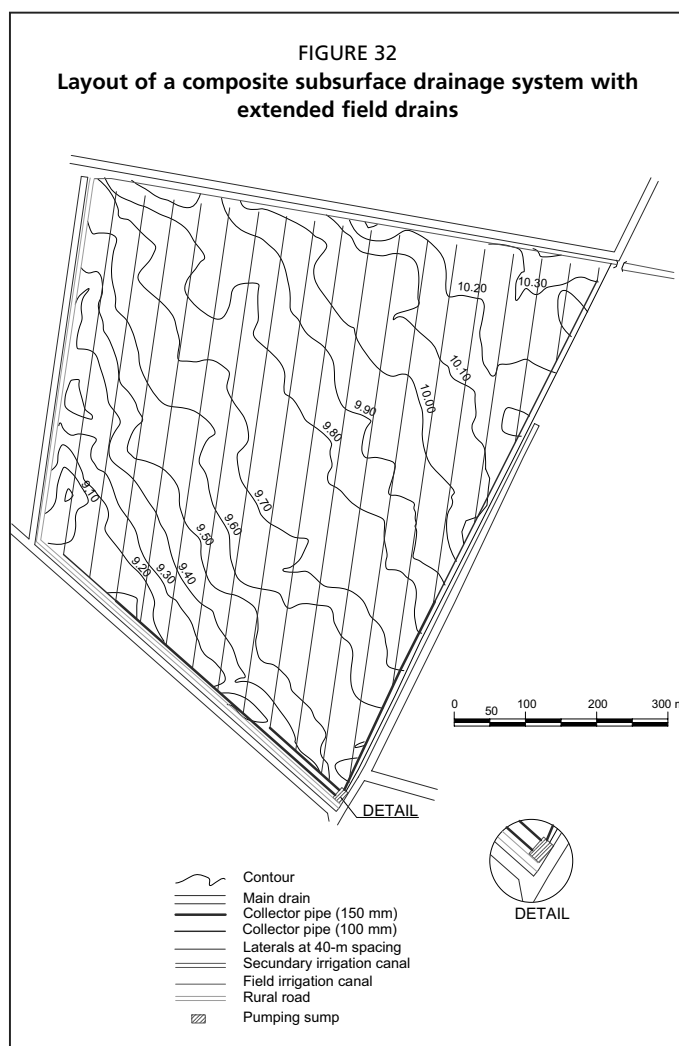


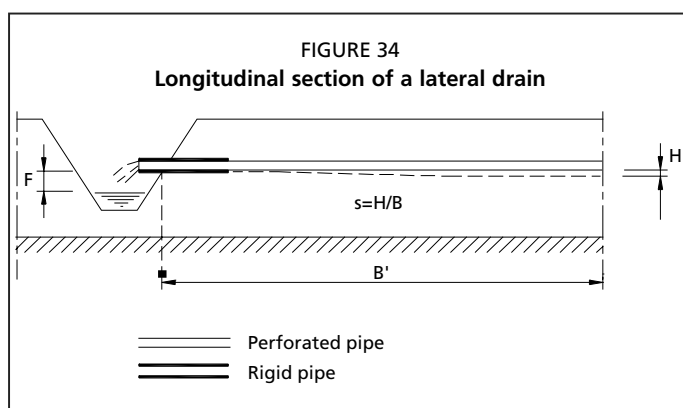
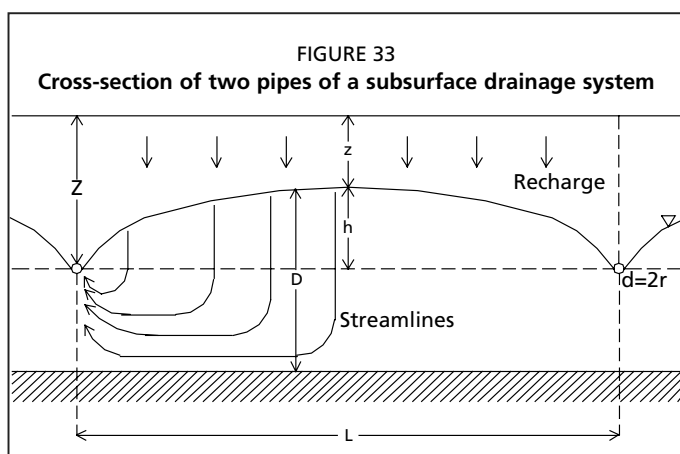
Controlled drainage is sometimes used to slow drainage during dry periods, and increasingly to control water requirements of rice in rotation with dry-foot crops. Then, the water table is maintained at a higher level by technical means, such as temporary plugs in subsurface drainage systems, raising seasonally the open drain water levels, or rising lateral/collector pipe outlets. Thus, a certain amount of water is saved from flowing away during droughts, or when fields are flooded during a rice crop. In Egypt, during rice cultivation in otherwise dry-foot crop cultivated land, such plugs are used to close the orifice in the bottom part of a specially constructed overflow wall inside inspection maintenance hatches of composite drainage systems. Water tables can also be controlled by subirrigation, where water from outside sources flows into the drain if the outside water level in the whole area is kept high for a considerable period. Apart from these uses, it is effective for preventing clogging with iron compounds, and the outflow of nitrates from the drainage system may be reduced by denitrification. However, great care should be taken with such systems in arid areas subject to salinization.

Although there are no physical restrictions on the length of subsurface field drains, it is usually governed by the size of the agricultural fields and the maintenance requirements of the drain. In composite systems, the same applies to the length of collectors. Where cleaning is required, the maximum length of pipes is usually limited by the maximum length of the cleaning equipment, which is about 300 m.

However, where there is enough slope and no constraints (owing to field dimensions) on designing pipe drains longer than 300 m, extended systems can be designed. However, they require a suitable access construction for cleaning devices at about every 300 m. As longer drains require larger diameter pipes, maintenance hatches should be installed to facilitate the connection between pipes of different diameters, as well as for inspection and cleaning, notably in the case of collector drains. Accessible junction boxes should be placed at the junctions between laterals and collectors.

Figure 32 shows details of an extended composite drainage system of the type installed in the irrigation districts of northwest Mexico. In this example, the pipe diameter changes only in the collector drains, and a second collector drain has been installed on the southern side instead of increasing again the diameter of the first collector drain.





## DESIGN CONCEPTS AND APPROACHES

In designing horizontal subsurface drainage systems, in addition to the drain length  $B$  described above, the following dimensions are needed:

- drain depth  $Z$ ;
- drain spacing  $L$ ;
- drain slope  $s$ , or total allowed head loss in the drain at design discharge intensity  $H$ ;
- drain diameter  $d$ .

Moreover, for composite systems, the dimensions of the collectors (depths, slopes and diameters) must be determined.

The type of pipes and possible types of protective drain envelopes must be selected, preferably from among the types and sizes that are readily available in the country. In addition, the method of installation (trenchless or in dugout trenches) and the method of maintenance must be chosen.

Figure 33 shows some drainage parameters (the average thickness of the groundwater-bearing layer  $D$  is also shown).

Figure 34 (longitudinal section) shows other dimensions of a field drain, such as the drain slope  $s$ , as well as the outlet structure into the open drain and its freeboard  $F$ .

The drain slope  $s$  is defined as the difference in elevation between the upstream and downstream ends  $H$  divided by the horizontal distance  $B'$ . However, for small  $s$ , the drain length  $B$  can be taken instead of  $B'$ . In practice,  $s = H/B$  is usually used. The difference is negligible where  $s < 0.01$ .

The design dimensions, such as the average drain depth, drain slope and allowed head losses, are usually the same for large areas, often over an entire project. Sometimes, they are prescribed quantities. On the other hand, drain spacings, lengths and pipe diameters may vary considerably from place to place, as spacings depend on crops and soil conditions, lengths on the system layout, and diameters on spacings, lengths and slope.

The lengths and diameters of field and collector drains depend considerably on the dimensions of the plots to be drained, thus on the parcelling of the area. Both are interrelated, as the longer the drains are, so the greater their diameter must be. As the price of pipes increases with diameter, in the case of long drains, where all diameters of pipes are readily available, it can often be profitable to begin upstream with smaller pipes, using increasing diameters further downstream. The switch in diameter has to be done at a logical place (maintenance hatch), otherwise mistakes can be made during installation and/or problems may occur with the cleaning of the drains.

The drain spacing is also related to cost. In singular drainage systems, the costs are almost inversely proportional to the spacing.

The drain spacing and the drain depth are mutually interrelated – the deeper the level of the drains so the wider the drain spacing can be. Thus, increased spacing

might lower the amount of the subsurface drainage work, and consequently the costs. However, in some cases, the cost advantages of greater drain depth may be offset by an increase in construction cost per unit length, by larger diameter of field drains, by higher costs of deeper collectors and ditches, and by costlier O&M, especially where deeper drains need a lower outlet level (which might indicate that pumping is necessary or pumping costs are higher). Moreover, deeper drainage is often restricted by other factors, e.g.: by soil conditions, as in heavy clay soils with shallow impervious layers; outside water levels, as happens in lowlands; or, less frequently, by the availability of appropriate machinery.

For example, in Egypt, during often relatively short fallow periods, groundwater must be lowered in order to limit topsoil salinization by capillary rise. Detailed cost calculations resulted in the conclusion that deeper and wider spaced drainpipe installation only entailed modest installation cost savings owing to the extra cost stemming from larger drain diameters (although the total installation cost was still lower compared with drains installed at a shallower depth). For example, a system where the water level between drains is designed at 1.50 m below field level with a hydraulic head of 0.30 m requires a drain depth of 1.80 m and drain spacing of 80 m. During the fallow period in this arid area, the actual water level between drainpipes will be slightly higher than 1.80 m. Where the pipes are installed at 1.60 m depth to fulfil the requirement of a water table at 1.50 m, the pipes have to be spaced at 50 m. This means a depth gain of only 20 cm, for a cost increase of about 60 percent. During the fallow period, the water table depth is then about 1.60 m (instead of 1.80 m). However, in the heavy clay soils of the Nile Delta, capillary rise is very slow, and as irrigated cropping intensity is high, both depths are sufficient to prevent soil re-salinization.

Once a design drain depth has been selected, there are two different approaches to calculating the drain spacings:

- for conditions of steady-state groundwater flow towards the drains, where the flow in wet periods is assumed to be constant in time;
- for non-steady-state flow conditions, where flow is time-dependent.

In the former case, an outflow intensity, which is assumed constant, is used as a criterion; in the latter case, the time to obtain a given drawdown after a critical recharge event is taken as design datum.

The steady-state method can be used where the recharge to the water table is approximately constant during a critical period. Then, it is possible to design the system with a discharge equal to the recharge. If, at a design water table height, the inflow of water to the soil is constant and equal to the drain outflow (so that storage effects can be ignored), the water balance in the saturated zone is in equilibrium and the groundwater level remains at a constant depth.

In practice, steady-state flow is a good approximation:

- in temperate zones with long periods of low-intensity rainfall that are critical for drainage;
- in areas recharged by deep upward seepage from a semi-confined aquifer;
- in areas where there is lateral seepage from outside waterbodies;
- in irrigated lands where water is continuously applied through high-frequency irrigation methods, such as drip irrigation and central-pivot systems.

The steady-state approach is less applicable where high recharges occur in a short period of time only, such as after heavy irrigation or sudden rainfall. In this case, the water balance is not in equilibrium as when the recharge is higher than the discharge, the groundwater level rises; and when the recharge ceases, the system is still draining, and the water level falls. The conditions where soil water storage is important in design are frequent in:

- areas with heavy showers of short duration, common in some Mediterranean areas and in the humid tropics;

- in irrigated lands with intermittent irrigation where applications of 60–120 mm are common.

However, under certain assumptions, non-steady drainage flow conditions can be converted mathematically to steady flow conditions. Therefore, steady flow considerations can be used as a substitute for processes that are essentially non-steady in nature.

Technical details for the steady and non-steady drainage design approaches are given below.

### **DRAINAGE CRITERIA**

In humid temperate areas, agricultural drainage must be able to prevent damage to crops in periods with abundant rainfalls occurring with a frequency of once in 2–5 years. In arid areas, drainage should prevent the accumulation of harmful amounts of salt and provide adequate drainage after a heavy irrigation or after heavy rains as occur in monsoon-type climates.

Artesian conditions (deep aquifers under pressure) often lead to upward seepage flow of water from deeper layers. This flow has a great influence on the design of a drainage system. It often makes a “normal” drainage unable to prevent waterlogging or salinization. Thus, extra measures are necessary in upward seepage areas. Where the seepage water can be reused, vertical drainage may be an option for controlling the water table.

Drainage requirements result in two important factors for drainage design, which are used in the steady-state determination of drain spacing: the specific discharge  $q$ ; and the hydraulic head midway between two drains  $h$ , which should be available for causing the required groundwater flow. This head represents the drain depth  $Z$  minus the required groundwater depth  $z$  (Figure 33).

For non-steady calculations, an additional input parameter is needed. This is the storage coefficient ( $\mu$ ) (described in Chapter 4).

Therefore, the dimensions of a subsurface system depend on the following drainage criteria:

- the design groundwater depth  $z$  or the depth of the water table below the soil surface, midway between drains, during times of design discharge (for crop season, fallow periods, etc);
- the outflow intensity  $q$  or the design discharge of the drains per unit area, and usually expressed in millimetres per day;
- in non-steady cases, the time in which the groundwater should regress from the initial high water tables (or complete inundation) to a given water table depth (midway between the drains) is used. This recession time depends on crop and temperature; for horticultural crops, it is usually short, especially under high temperatures.

Fundamental criteria such as design groundwater depth and design outflow are derived from guidelines, local experience, research plots, theoretical considerations and models. For example, the DRAINMOD model (Skaggs, 1999) allows evaluation of criteria or checks on those derived by other means.

The following sections provide some indications for values of these drainage criteria.

#### **Design groundwater depth**

Critical to crop growth and soil trafficability is the depth at which the groundwater remains/fluctuates under critical circumstances. At design discharge for field crops, this depth  $z$  is usually of the order of 0.9 m, but it varies by crop, soil and climate. For shallow-rooting horticultural crops on pervious soils, depths of 0.5 m may be reasonable. Tree crops require greater depths than vegetables, but the latter can stand

water near the surface only for a few hours and, thus, are vulnerable to extreme high water table situations, especially when temperatures are high.

In temperate zones, controlled drainage permits two design groundwater depths: a deep depth to provide aeration and trafficability in periods with excess of water; and a shallower depth to facilitate subirrigation in dry periods. Controlled drainage also permits high water levels for nitrate reduction and preventing iron precipitation in the pipes.

In climates with low-intensity rainfall, the following minimum depths to the steady-state design groundwater depth (midway between drains) during short wet periods are usually recommended:

- 0.3–0.5 m for grassland and field crops for design outflows of about 7–10 mm/day;
- 0.5–0.6 m for vegetables grown on sandy loam soils.

In arid areas, two design depths are frequently required: one during the cropping season to provide aeration to the rootzone (unless rice is grown); and a second one for fallow periods in order to prevent capillary rise and associated salinization (where seepage from irrigation elsewhere would cause too high groundwater levels). As the drainage discharge is also different during the cropping and the fallow seasons, the drain spacing/depth has to be designed for the most critical period (the smallest  $b/q$ ), bearing in mind the required groundwater depth during the fallow period (smaller  $b$ , lower  $q$ ).

In irrigated lands, the following design depths for groundwater for steady-state design outflow (in dry climates, e.g. 2 mm/d) can be used as a starting point:

- 0.8–0.9 m for field crops;
- 1.0–1.2 m for fruit trees, depending on soil texture.

In the case of irrigation of rice, controlled drainage permits the elevation of the groundwater level up to the ground surface in order to prevent excessive water losses. Here, there is no danger of salinization owing to the absence of upward flow in the inundated soil.

To control capillary rise and related soil re-salinization processes, groundwater must remain below a certain depth in periods without rain or irrigation. This safe design depth is determined mainly by the capillary properties of the soil and the salinity of the top layers of the groundwater mound. In particular, silts and silt loams require deep drainage.

Where the critical depth to control capillary rise is excessive and higher groundwater levels have to be accepted, then, in order to secure acceptable soil salinity levels, the salts accumulated during the fallow period must be leached by irrigation where there is no excess rainfall.

### Design outflow

In humid temperate areas, the design discharge occurring with a frequency of once in 2–5 years is usually taken as the design criterion. Under these circumstances, crops should not suffer from waterlogging.

In arid climates, prevention of salinization is the main purpose of drainage, and for most cases a discharge capacity of 2–4 mm/d is sufficient for leaching. Annex 7 provides details on design discharge for salinity control in irrigated land.

In humid tropical areas (including those with monsoon climates), the rains are often so heavy that the infiltration capacity limits recharge, and surface runoff may occur. In addition, the subsurface drainage system is usually unable to cope with the inflow. The same applies to other climates with intense rains. In such cases, a combination with a surface drainage system is needed. After the rains, when the soil is saturated, the subsurface drainage system then lowers the groundwater to a sufficient depth in a reasonable time (non-steady state, see below), whereas in the dry season it prevents the accumulation of salts.

TABLE 8  
Examples of design discharges

Climate	$q$ (mm/d)
Humid temperate climates	7–15
Humid tropical climates	10–15
Irrigated lands in arid climates	1–2

models is recommended. To indicate the order of magnitude, Table 8 gives some examples of design discharges in current use.

Where considerable seepage occurs, the amount of seepage water must be added to the design discharge, and the pipe sizes adjusted accordingly. For example, this is the case where relief wells are used to tap the aquifer – the drains must be able to convey this extra amount of water.

### Groundwater lowering

In the non-steady-state design method, both  $z$  and  $h$  are functions of time. After a heavy rain or irrigation, the groundwater should fall a given depth in a given time so that its depth  $z$  increases (e.g. 0–0.30 m in 4 hours for vegetables). Because  $Z$  cannot change with time,  $h$  also falls by the same amount. Such a requirement can be used to calculate drain spacings. In this non-steady case, the storage coefficient and not the discharge is used as an input parameter. In this case, the drain discharge rate varies with time.

Where heavy rains or irrigation have caused water to stand on the surface, the following criteria for the lowering of the groundwater could be used under non-steady flow:

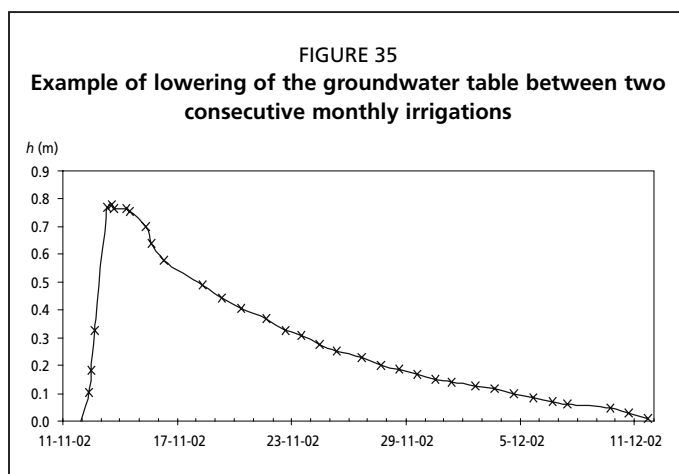
- for horticulture, a lowering after complete inundation of 0.30 m in 4–6 hours;
- for most crops in hot climates, a lowering of 0.30 m in 1 day;
- in cool climates, a lowering of 0.20 m in 1 day.

In irrigated lands, in addition to these criteria, the soil provides storage for the percolation water, and the drainage system must be able to remove this storage before the next irrigation. Therefore, between two irrigation applications, the drawdown of the water table must be similar to the elevation produced by the irrigation water losses (Figure 35). A low outflow criterion (e.g. 2 mm/d) is usually sufficient for this purpose.

For example (Figure 35), where 40 mm of percolation is stored in a soil with a storage capacity of 5 percent, this gives a rise of 0.8 m. The groundwater level

must be low before the following irrigation, for example 30 days, and the stored water must be removed in this period, requiring on average a drainage coefficient of 1.3 mm/d.

Under these circumstances, the best approach is to design the system with a steady-state method and a low outflow intensity, and then to simulate its behaviour after complete flooding. If the outcome is not satisfactory, the steady-state discharge must be changed by increasing the steady outflow criterion. This will lead to a narrower spacing, which can be tested again



for its non-steady behaviour. The process is repeated until a satisfactory solution is obtained.

### SYSTEM PARAMETERS

#### Drain depth

The selection of the drain depth is a crucial and early decision in a drainage project. This is because of the technical aspects involved, and because of the direct influence of

the drain depth on the overall cost of the system. As mentioned above, deeper drains allow wider drain spacings with fewer drains per unit area, but other factors, such as construction and O&M costs of field and main drains and outlet structures, play a role in the overall cost.

The depth of the laterals  $Z$  is equal to the sum of the depth to the water table  $z$  and the hydraulic head  $h$  both taken midway between two drains (Figure 33). Under steady-state conditions, the required groundwater depth must be adjusted by the head loss  $h$  required to cause groundwater flow towards the drains:

$$Z = z + h \quad (8)$$

or, with a given drain depth, limited by the discharge level, etc.:

$$h = Z - z \quad (9)$$

where:

$h$  = head loss for flow in soil, at design discharge (m);

$z$  = groundwater depth midway, at design discharge (m);

$Z$  = drain depth (m).

As mentioned above, the design value for  $z$  depends on climate, crop requirements (crop calendar, rooting depth, crop salt tolerance), and soil and hydrological conditions. Moreover, to select an adequate drain depth  $Z$ , the hydraulic conductivity and the soil stability of the layers situated above the impervious barrier should be considered (because drains should not be installed in or below impervious layers). Unstable soils such as quicksand are to be avoided. Although quicksand can be handled, it requires a special installation technique with sometimes modified machines. In addition, the drain depth is often limited in practice by the water level at the outlet of laterals or collectors into the main drainage system.

The minimum depth of open trenches for subsurface drainage is about 0.6 m, and for pipes it is about 0.8 m. Pipes installed at a shallower depth may become clogged if crop or tree roots (orchards; windbreaks) penetrate into the drain through the pipe slots. In addition, shallow pipe drains can be damaged during subsoiling operations, which are common in the management of clay soils with low permeability. In cold climates, pipes must be deep enough to prevent freezing. Table 9 gives some indications of commonly applied depths of installation pipe drains.

#### Drain spacing

Drain spacing is an important factor because the cost of subsurface drainage is related closely to the installed length of drains per unit area:

$$C = \frac{10000}{L} C_u \quad (10)$$

TABLE 9

Examples of depths of pipe lateral drains

Region	Drain depth (m)	Remarks
Temperate	1.0–1.5	from 1.0–1.2 m in rainfed areas to 1.0–1.5 m in irrigated lands
Humid tropical	0.8–1.5	
Arid (sandy soils)	1.0–1.5	capillary rise is limited in height
Arid (clay soils)	1.5–2.0	capillary flow is very slow
Arid (silt loam soils)	2.0–3.0	capillary rise and seepage of saline water are major concerns

where:

$C$  = installation cost of the system (in terms of monetary units per hectare);

$C_u$  = cost per unit length of installed drains (in terms of monetary units per metre);

$L$  = drain spacing (m).

Although the field drains form a major component of the cost, collectors and the main drainage system are important items, as are the capitalized costs of O&M. Therefore, if it is decided to install deeper drains to allow wider spacings, the additional costs of the required deeper main system must be compared with the savings on field drains.

There are various methods of calculating drain spacings from the drainage requirements and the soil characteristics. Of these, the soil permeability, the layering and anisotropy are especially important factors (Chapter 4). The calculation methods fall into the two categories mentioned above: steady and non-steady flow. In steady-state calculations, the inputs (apart from the soil data) are the design head loss  $h$  or midpoint water table height and the design discharge  $q$ . In the non-steady case, the design factors comprise a prescribed increase in groundwater depth  $z$  with time in combination with the storage coefficient  $\mu$ .

Steady-state methods may form a first step in designing drain spacing, but non-steady methods can represent the changing conditions more accurately. Therefore, as a second step, drain systems designed tentatively with steady criteria may be subjected to more realistic, variable inputs in order to evaluate the design. In this way, the design can be tested and adapted as necessary.

Annexes 17 and 19 describe the respective drainage equations for steady and non-steady groundwater flow that are commonly used for drain spacing calculations. Where vertical seepage is relevant, the Bruggeman method (Annex 18) can be applied.

Chapter 8 and Annex 23 provide descriptions of available computer programs for designing subsurface drainage, and some calculation examples.

The distance between two parallel laterals may vary between 50 and 150 m in permeable soils. In pervious clay soils, spacings of 20–50 m are common; in heavy clay soils and certain silt loams, spacings of 10–20 m are frequently required (Martínez Beltrán, 1999). In irrigated lands with an arid climate, the drain spacings are usually much wider than under rainier conditions owing to smaller discharges of the drains.

### Drain slope and allowed head loss in the pipes

The cost per unit length of installed field drains  $C_u$  (Equation 10) is related closely to the drain diameter. This diameter depends on the expected outflow and on the available hydraulic head difference along the drain. Consequently, the drainpipe might be constructed without any slope. However, for practical reasons (e.g. to reduce the incidence of sunken pipe stretches which silt up easily and may ultimately cause blocked pipes) and cost-saving considerations, slopes are designed as high as possible in order to minimize the drain diameter.

In sloping lands, drains can be laid parallel to the ground slope, especially where the surface has been graded. Thus, the pipe depth is maintained along the drain. The usual criterion for sloping drains is that, at design discharge, no water is standing above the drain at its upstream end. However, interceptor drains, intended to collect and remove seepage water entering the top of the field, should follow the groundwater or soil surface contours.

In flat lands, a shallower drain depth of the upper end of the drain must be chosen in order to maintain a minimum slope. However, very small slopes (even horizontal drains) are possible, if the drains are constructed carefully and are sometimes used if subirrigation is to be practised. In such horizontal drains, water must be allowed to temporarily stand above the drain in wet times, which by itself is not a problem as long



as it remains deep enough below the soil surface. The argument that slope is needed to transport sediments out of the lateral is valid only at slopes of more than 1 percent, which are seldom possible in flat lands where drain slopes are usually in the range of 0.1 to 0.3 percent. Such a flat slope is not enough to remove incoming soil by the water flow. Therefore, precautions against clogging are needed, i.e. careful construction of the drains and, in many cases, the use of protective drain envelopes.

However, horizontal drains are not recommended because the installation tolerances are never negligible even where the drainage machine is equipped with a laser device. In practice, minimum slopes of 0.07 percent or in extreme cases 0.05 percent can be considered.

### **Drain diameter**

The design of the drain diameter should take into account the available diameters and the costs thereof. As cost increases with diameter, finances play a role in the choice of diameter.

In designing the drain diameter, the total head loss in the drain during a very wet period  $H$  is considered. It is often required that, at design discharge, no water be standing above the upstream end of the drain. Therefore, with a slope of 0.2 percent and a length of 250 m, the available head for pipe flow is 0.50 m. If in flat land the drain outlet is 1.50 m below the surface, the depth of the drain at the upstream end will only be 1.00 m. With an allowed head loss of 0.50 m, there will be no water above the pipe. In this case, drain slope and allowed head loss are the same. However, the same drain with the same outlet depth, but with a slope of 0.10 percent, has an upstream depth of 1.25 m below surface. With an allowed head loss of 0.50 m, there will be 0.25 m of water standing above the drain at design discharge, but the depth of this water will also be 1.00 m. The same reasoning applies to any slope below 0.2 percent and even for a horizontal drain. This example shows that there is no direct relation between drain slope and allowed head loss. Therefore, the allowed head loss in the pipes will be taken as an input for calculations of the required drain diameters. This head loss determines the groundwater depth near the drain during critical times at the least favourable places.

The diameter of lateral and collector drains can be calculated using various formulae, which are based on the laws for pipe flow. These calculations are different for smooth and corrugated pipes, because of pipe roughness. The available head loss at design discharge and the amounts to be drained under that condition form the base for calculations concerning pipe diameters. Annex 20 describes formulae commonly used for drain diameter calculations. Description of available computer programs is also given in Chapter 8 and, in more detail, in Annex 23.

Pipes with an outer diameter of 80–100 mm are common for wide drain spacings; 65–80-mm pipes are frequently used in systems in the temperate regions; and 50–65-mm pipes are used in drainage systems for clay soils.

## **DRAINAGE MATERIALS**

FAO Irrigation and Drainage Paper No. 60 (FAO, 2005) provides full details about materials for subsurface drainage and their use. Therefore, only limited reference is made here.

### **Pipes**

Corrugated plastic pipes with adequate perforations are most frequently used as field drains because of their flexibility, low weight and their suitability for mechanical installation, even for a drain depth of 2.5 m and more. Polyvinyl chloride (PVC) is commonly used in Europe, and polyethylene (PE) pipes are commonly used in North America, but both are technically suitable. Although PE material is less resistant

to soil loading than PVC and is sensitive to deformation at high temperatures, it is more resistant to ultraviolet radiation during storage and handling, and is less brittle at temperatures below 3 °C. However, the choice is usually based on availability and price considerations.

Water enters into the drainpipe through perforations. These openings are uniformly distributed in at least four rows. The perforated area varies from 1 to 3 percent of the total pipe surface area. Where the perforations are circular, diameters range from 0.6 to 2 mm. Elongated openings have a length of about 5 mm. In Europe, the perforation area should be at least 1 200 mm<sup>2</sup> per metre of pipe (FAO, 2005).

Baked clay or concrete pipes about 30 cm long are still sometimes used, the former for field drains, and the latter mostly for large collector drains, especially where the required diameter is more than 200 mm. These pipes may be considered as “technically smooth”. Clay tiles have a circular cross-section with an inside diameter of 50–200 mm. For collectors, the inside diameters of concrete pipes range from 100 mm upwards. Where the diameter is more than 300 mm, reinforced concrete should be used. Where the sulphate content of the groundwater is high, it is necessary to use high-density cement resistant to gypsum. Additional details for clay and concrete pipes can be consulted in FAO (2005).

Drainage pipes should fulfil technical specifications that are verified in laboratories before installation. For plastic pipes, these specifications include impact resistance, weight, flexibility, coilability, opening characteristics and hydraulic characteristics (and with concrete pipes, resistance to sulphates). The draft European standard on corrugated PVC pipes has been published by FAO (2005).

### **Pipe accessories and protection structures**

At the upstream end of the drain, caps are used to prevent the entry of soil particles. Snap-on couplers are used to connect plastic pipes of the same diameter, and plastic reducers are used where the pipes are of different sizes. Where couplers and end caps are not available, the drainpipes can be manipulated in the field to fulfil the same functions.

Rigid pipes, of sufficient length to prevent the penetration of roots of perennial plants growing on the ditch bank, are used as outlets. These pipes are also used where a drain crosses unstable soil, or a row of trees that may cause root intrusion.

Details on pipe accessories and protection structures are described in FAO (2005).

### **Envelopes**

To prevent soil intrusion in unstable silt and sandy soils, drainage pipes should be surrounded by envelope material. Envelope material can be made of: fine well-graded gravel; pre-wrapped organic materials, such as peat, or natural fibres, such as coconut fibres; or woven and non-woven synthetic materials, such as granular polystyrene and fibrous polypropylene. In soils consisting of stable clays at drain depth, such envelopes may often be omitted, which reduces drainage costs.

Envelopes prevent the entrance of soil particles, but they also promote the flow of water into the drain. A good envelope conveys water to the perforations, thus considerably reducing the entrance resistance. Moreover, voluminous envelopes increase the effective radius of the drain, from the pipe radius to that of the pipe plus envelope thickness. This further promotes water flow and improves the hydraulic efficiency of the drain.

In addition to the entrance resistance restriction by soil clogging, drainage pipes have to face other problems, such as clogging of the pipe openings by penetration of roots into the pipe, by biochemical processes such as ochre formation, and by precipitation of less-soluble salts, such as gypsum and carbonates, which are difficult to prevent.

It is not easy to predict the need for an envelope but tentative prediction criteria are available. These criteria are based on clay content, soil particle size distribution, and salt and sodium content of the soil solution.

Fine, well-graded gravel forms an excellent envelope, but the high cost of transport and installation constrains its use in practice. Organic fibres may decompose with time. Therefore, synthetic envelopes, such as pre-wrapped loose materials and geotextiles with appropriate opening sizes, are in widespread use.

Envelopes should also fulfil technical specifications, such as: thickness, mass per unit area, characteristic opening size and retention criteria, hydraulic conductivity and water repellence, and some mechanical properties.

Guidelines for predicting the need for envelopes and for selection of the appropriate material are available (FAO, 2005; Vlotman, Willardson and Dierickx, 2000), but the selected material must be field-tested for local conditions. Requirements for envelopes used for wrapped pipes are also included in the draft European standard (FAO, 2005).

### Auxiliary structures

Where singular subsurface drainage systems are used, a rigid outlet pipe (Figure 36) is necessary. The rigid pipe should be long enough for water to flow directly into the outlet drain ditch water in order to prevent erosion of the ditch bank and to impede clogging by roots of bank vegetation. As these pipes hamper mechanical ditch cleaning, the bank may also be protected by concrete or plastic chutes.

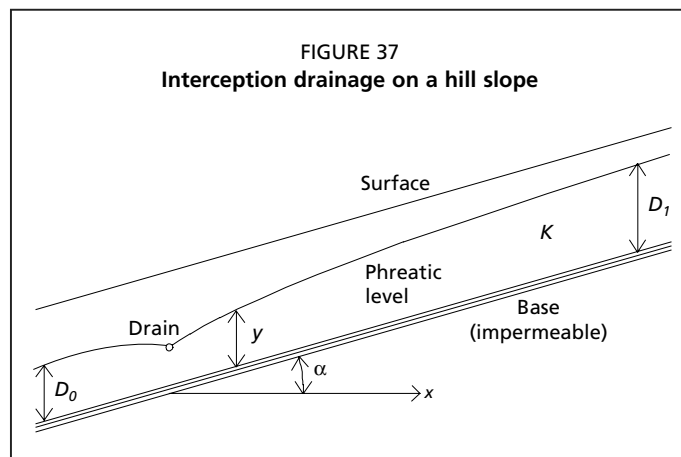
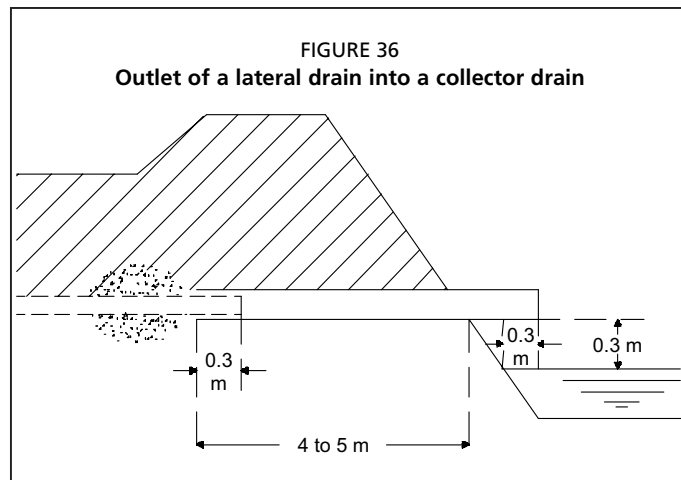
In composite subsurface drainage systems, cross-connectors, T-pieces and elbows are used to join buried laterals and collectors. Junction boxes or fittings are used to connect pipes where the diameter or the slope of the pipe changes. Where inspection and cleaning are required, maintenance hatches replace junction boxes.

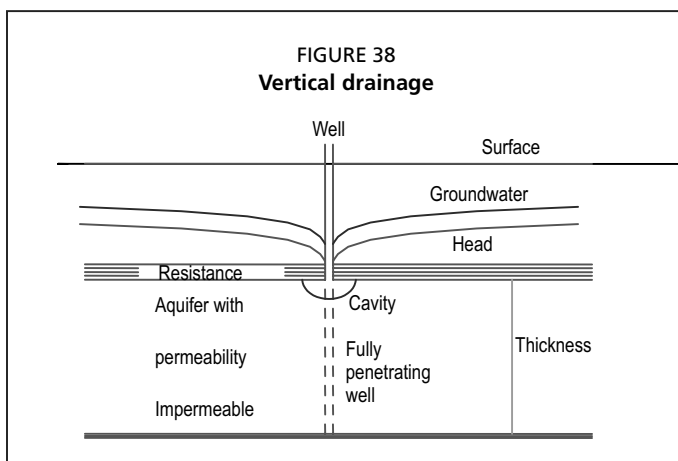
Blind and surface inlets can be used to evacuate surface water through subsurface drainage systems. However, provision should be made to prevent entry of trash and eroded soil by using appropriate envelope material.

Details on connection structures, outlets and special structures on pipe drains for controlled drainage are described in FAO (2005).

### INTERCEPTION DRAINAGE

Inflow from higher places (Figure 37) or from leaky irrigation canals can sometimes be captured by interceptor drains, especially where it passes through relatively shallow aquifers. The effect of interception drainage is only significant if the





impermeable layer is about at the drain depth. Otherwise, the effect is roughly only proportional to the percentage that the interceptor drain depth is of the thickness between the phreatic level and the impermeable layer.

Interceptor drains can take the form of pipes or open ditches. However, with the latter, the stability of the side slopes is often problematic where large volumes are to be captured. Better solutions are gravel-filled trenches provided with a suitable pipe of sufficient capacity to carry the discharge.

Annex 21 provides further details and calculation methods, and Chapter 8 describes a computer program (more detail in Annex 23).

### Vertical drainage

Vertical drainage is achieved by an array of properly spaced pumped wells that lower the head in an underlying aquifer (Figure 38) and lower the water table.

Vertical drainage can be used successfully under special physical circumstances:

- the presence of a good aquifer underneath (unconfined or semi-confined), so that wells give a good yield;
- a fair connection between the soil to be drained and the aquifer, so that the lowered head in the aquifer results in a lower groundwater table. The layers between the aquifer and soil to be drained must be permeable enough to convey the recharge of the groundwater by rainfall and irrigation losses to the aquifer. In other words, the resistance between groundwater and aquifer must not be too high;
- the system should be sustainable.

The aquifer should not be pumped dry. Where the water is to be used for irrigation or for municipal supply, a suitable quality is required that must not deteriorate rapidly with time. This sometimes occurs because vertical drainage may attract salt from deeper layers (where the deeper parts of the aquifer are brackish or saline, in which case, vertical drainage can only be a temporary solution). Chapter 2 has already addressed the other water quality aspects, e.g. the presence of toxic substances.

As constant pumping is needed, the O&M costs are rather high. This leads to the following economic restrictions:

- The method is only economically viable where the pumped water is fresh and can be used for the intended purposes. However, mixing with better quality waters can sometimes be a solution where undiluted use is not allowed.
- Where the water is too salty, it causes disposal problems in the project area that need special provisions. These add to the costs, making vertical drainage still more uneconomic in these cases.
- The O&M costs and complexities of relatively dense well-fields limit the application of vertical drainage.

Despite these constraints, the method is applied widely in some areas where the soil and aquifer conditions are favourable and where the pumped water can be used. In such areas, it has often led to a depletion of the aquifer and sometimes to extraction of salts from deeper layers.

Vertical drainage may also be an option in locations with severe seepage problems. Here, pumping is not always needed, because of overpressure in the aquifer. Where

technically feasible, vertical extensions of a horizontal drainage system may be a cheap substitute.

Relief wells consist of vertical wells that reach slightly into the aquifer. In a drain trench, vertical boreholes are made into the aquifer and provided with blind-ended perforated pipes as well casings. They are usually made of corrugated plastic and are the same as the drain itself. These pipes are connected with the horizontal laterals by T-junctions. The method has been successful in several cases. However, the extra discharge of water may be a burden for the outlet system, and its salinity may harm downstream users.

Annex 22 provides details on the design and calculation of vertical drainage systems. A computer program for drainage by vertical wells is described in Chapter 8 (more detail in Annex 23).

## Chapter 8

# Calculation programs for drainage design

### INTRODUCTION

Since the advent of the electronic computer, models have found wide application. For drainage, various models are used in research and engineering (Table 10). Universities and research institutes have developed sophisticated models, and governmental institutes, engineering companies and individual consultants use various calculation methods for design. Information on applications of GIS for planning and design of

land drainage systems can be consulted in Chieng (1999). Computer programs for drawings, such as topographic and layout maps, and detailed design of open drains and ancillary structures of the main drainage system are widely used by engineering firms. Additional information on computer applications related to land drainage is given in Smedema, Vlotman and Rycroft (2004).

The CD-ROM version of this FAO Irrigation and Drainage Paper includes several programs for drainage design, largely based on formulae given earlier in this publication. The aim is not to clarify the underlying fundamentals or provide great sophistication, but rather to facilitate their direct application to drainage design under practical circumstances. In addition, some related problems are addressed that have influenced the design itself, such as backwater effects and seepage (as described in earlier chapters).

The programs are in FORTRAN and run under both Microsoft Windows and DOS. Inputs are in the form of questions and answers. Choices between various possibilities have to be made by typing certain numbers, and input data have to be provided in the same way. The units are metric, in accordance with FAO standards.

### GENERAL STRUCTURE

The programs have a common basic structure, allowing easy retrieval. For this purpose, certain rules have to be followed regarding notation of decimals, the abbreviated name of the project and the location.

The following items are considered:

- The program mentions its name and purpose in order to check that it is appropriate. If not, it can be terminated easily.
- A point must be used as decimal separator. A question is raised about national usage; if a comma is the norm, a warning is given.
- A “project” name of a maximum of four characters is required (letters or numbers in single quotes). This shortness is because of the restricted length of filenames under DOS.
- Within this project, several locations can be used, each of which characterized by a name of a maximum of ten characters in single quotes (letters or numbers).

TABLE 10

Some models involving drainage

Model	Reference	Remarks
DRAINMOD	Skaggs, 1999	extensive model for drainage
DUFLOW	STOWA, 2000	non-steady one-dimensional canal flow
ESPADREN	Villón, personal communication, 2000	calculates drain spacings using several formulae, in Spanish
SAHYSMOD	ILRI, 2005	influence of aquifer on seepage, drainage and salinity
SWAP	Van Dam <i>et al.</i> , 1997	extensive model for saturated/unsaturated soil including drainage

TABLE 11  
Programs and file listing

Program	Background	Description	Purpose
<b>Extreme values</b>			
GUMBEL	Annex 2	Annex 23	Extreme values (rainfall, discharges)
<b>Calculation of permeability</b>			
AUGHOLE	Annex 3	Annex 23	Permeability from auger-hole data
PIEZOM	Annex 3	Annex 23	Permeability from piezometer data
<b>Spacing of drainpipes and wells</b>			
SPACING	Annex 17	Annex 23	Steady-state flow
ARTES	Annex 18	Annex 23	Drainage under artesian pressure
NSABOVE	Annex 19	Annex 23	Non-steady flow, above drains only
NSDEPTH	Annex 19	Annex 23	Non-steady flow, also below drains
NSHEAD	Annex 19	Annex 23	Non-steady flow, heads given
WELLS	Annex 22	Annex 23	Vertical drainage by well network
<b>Drain diameters</b>			
DRSINGLE	Annex 20	Annex 23	Single drains, one diameter
DRMULTI	Annex 20	Annex 23	Multiple drains, various diameters
<b>Main drainage system</b>			
BACKWAT	Annex 10	Annex 23	Backwater effects on main system
<b>Interceptor drains</b>			
INCEP	Annex 21	Annex 23	Homogeneous profile
INCEP2	Annex 21	Annex 23	Drain or ditch in less permeable topsoil

- At the end of the session, the project receives a unique name for the output file, showing the results for the various locations.
  - For easy retrieval, all filenames are listed in a file LIST\*\*, where \*\* indicates the kind of program used (e.g. SP for drain spacings).
- Annex 23 provides further details. Table 11 lists the different programs.

## SPECIFIC PROGRAMS

### Extreme values

#### *GUMBEL*

Extreme values are the largest and smallest elements of a group. In many cases, they obey Gumbel's probability distribution. Applications are: the highest precipitation in a certain month and the highest discharge of a river in a year.

The program GUMBEL allows an easy method for interpolation and extrapolation. For a given return time, it calculates the value to be expected. A graph is shown to enable visual inspection of the fit of the data and a possible trend. A poor fit indicates uncertainty in the basic data; a distinct upward (or downward) trend that the data do not obey the GUMBEL distribution and that the extrapolated values are far too low (or too high). In this case, other methods must be used.

By extrapolation, a prediction can be given for return periods of 100 or 1 000 years. However, the uncertainty becomes considerable at such long times. Nevertheless, such extrapolation is valuable for engineering purposes, such as for the height of river embankments needed to withstand a "100-year" flood. The flood will almost certainly not take place after 100 years, but it has a probability of 1 percent of occurring next year (and maybe tomorrow) and has a good chance of occurring in a lifetime. Last, it must be borne in mind that natural and human-induced changes may influence the events in question. Examples are: the increase in impermeable surfaces (roads and cities) and deforestation will increase drainage flows; and climate changes (whether natural or human-induced) will have either positive or negative effects.

For drainage design, return periods of 2–10 years are often taken (2–5 years for agricultural field systems, 5–10 years for the main system), but these must be far higher

if human safety is involved. For example, in the Netherlands, return periods up to 10 000 years are used for sea dykes in critical areas.

The theory can be found in Chapter 4 (with more detail in Annex 2). Annex 23 provides details about the use of the programs and examples.

### Calculation of permeability

#### *AUGHOLE*

The auger-hole method is widely used for measuring soil permeability. The water level in an auger hole is measured before pumping, and afterwards its rise is determined. In dry soils, the fall of the water level after filling can be observed, but this “inverse” method is less reliable. Moreover, some soils swell slowly and have a much lower permeability in the wet season than when measured dry.

The program AUGHOLE can process the data obtained for both the normal and inverse methods. The results within the same auger hole are usually quite consistent. Where more than one observation is made in the same hole, the program takes the average and gives its standard error. When large variations are encountered, a message appears: “Not reliable”.

Between different holes, even nearby ones, differences may be considerable owing to local soil variations. However, in predicting drain spacings, these errors are diminished because the resulting spacings are proportional to the square root of  $K$ .

The resulting  $K$  values can be used as input for programs such as SPACING and the NS series.

The principles and the basic equations are given in Annex 3. Annex 23 provides details about the use of this program and an example.

#### *PIEZOM*

In an open auger hole, a kind of average permeability is measured for the layers between the groundwater level and the bottom of the hole. Where data are required for a specific layer, Kirkham’s piezometer method can be used. The auger hole is covered by a tightly fitting pipe, and, with a narrower auger, a short open cavity is made below its open bottom. Alternatively, an auger hole is covered partially by the open pipe and the remainder forms the cavity below. In the former case, the diameters of pipe and cavity are different; in the latter, they are almost equal. As with the auger-hole method, water levels are measured at different times. The permeability is measured of the layer in which the cavity is located.

The underlying theory is explained in Annex 3. The program PIEZOM can find the permeability from the collected data. Annex 23 provides details about the use of this program and an example.

### Spacing of drainpipes and wells

#### *SPACING*

This program includes an earlier program for the Töksös–Kirkham equations (J.H. Boumans, personal communication, 1999).

The program allows the calculation of spacing of pipe drains under steady-state conditions in cases where upward or downward seepage towards deeper layers is insignificant. If such seepage is considerable, ARTES must be used instead. If non-steady situations have to be considered, a preliminary steady-state solution by SPACING can be checked with programs from the NS series.

In SPACING, up to five soil layers can be considered, and anisotropy may be accounted for. However, in practical cases, sufficient data are seldom available and estimations are usually needed. Nonetheless, the effect of additional layers and anisotropy can be investigated by entering trial values.



The theory is given in Annex 17. Annex 23 provides details about the use of this program and an example.

### ***NSABOVE, NSDEPTH and NSHEAD***

These programs analyse the non-steady behaviour of a proposed or existing drainage system after complete or nearly complete saturation of the soil after heavy rainfall, snowmelt or irrigation.

NSABOVE can be used if the drains are at the impermeable base, so that the flow is above drain level only. The program gives the expected lowering of the groundwater table from zero to a given depth within a given time. These data can be based on agricultural requirements that depend on the tolerance of the crop or on soil tillage and trafficability needs.

NSDEPTH is used if also deeper layers take part in the drainage process. As in NSABOVE, the criterion is the lowering of the groundwater. It uses numerical calculations, and allows inclusion of the radial and entrance resistances near the drainpipe and the limited outflow capacity of the drainpipe and the main drainage system.

NSHEAD is similar to NSDEPTH but mentions the head above drain level instead of the water depth.

The related principles and equations are given in Annex 19. Annex 23 provides details about the use of these programs and examples.

### ***ARTES***

Artesian conditions may cause upward seepage where a deeper lying aquifer is under pressure, or natural drainage (downward seepage) where the pressure is lower than the pressure of the shallow groundwater. These conditions can exert a large influence on the layout of a subsurface drainage system. Strong upward seepage can lead to failure, whereas natural drainage can diminish the required intensity and even make subsurface drainage unnecessary.

In principle, geological information and a model such as SAHYSMOD are needed. However, for a first estimate, ARTES can be used to see whether serious effects are to be expected. At this stage, good data about the aquifer and the top layer are seldom available, but estimates can provide some insight about the effects to be expected. The program gives two solutions – one for a wet and one for a dry season. The latter is usually critical because of capillary rise and salinization hazards.

The principles and the basic Bruggeman equations are given in Annex 18. Annex 23 provides details about the use of this program and an example.

### ***WELLS***

Instead of drainage by a network of pipes or open channels, a network of wells may be used (vertical drainage). However, this method can only be used under specific circumstances:

- A good aquifer must be present.
- This aquifer must have sufficient contact with the overlying soil, so that pumping can influence the groundwater levels.
- There must be no danger of attracting brackish or saltwater from elsewhere.
- Overpumping must be avoided, although it may be allowed temporarily.

Under favourable circumstances, such a network may be useful. The program provides a simple approach for steady-state conditions. However, a more sophisticated method, based on geohydrological studies, is recommended for estimating the effects such as overpumping and salinization.

The principles and equations are given in Annex 22. Annex 23 provides details about the use of this program and an example.

### **Drain diameters**

#### ***DRSINGLE and DRMULTI***

For long drains and wide spacings, and especially for collectors, it is often more economical to start with a small diameter and change to a larger size further on. Moreover, different materials may be used in the same drain. The program DRMULTI calculates such “multi” drains. Which of the two programs should be chosen depends on the local availability of pipes and on local prices.

The theory of drainpipe flow is given in Chapter 7 (more detail in Annex 20). Annex 23 provides details about the use of these programs and examples

### **Main drainage system**

#### ***BACKWAT***

Where the main system discharges into a river or the sea, or indeed any waterbody that shows fluctuations in water level, backwater effects occur. Especially during high outside levels, they interfere with the discharge from above. Open outlets may even allow a rapid flooding of the area.

The program gives an initial steady-state approach to such backwater effects. It gives the steady backwater curves, positive at high outside levels, negative at low ones.

The theory is given in Chapter 5 (more detail in Annex 10). Annex 23 provides details about the use of these programs and examples.

### **Interceptor drains**

#### ***INCEP and INCEP2***

In undulating terrain, waterlogging and salinization often occur at the foot of slopes or below higher irrigated or rainfed lands. Stagnation of groundwater also occurs in places where the thickness of an aquifer or its permeability diminishes suddenly. This may be caused by the presence of a rock sill. A related problem is the interception of water leaking from irrigation canals (although then an improvement of the irrigation system is a better solution).

The programs calculate the width of a drain trench or ditch sufficient to cope with the intercepted flow. INCEP is valid for a homogeneous profile, INCEP2 for a drain or ditch located in less permeable topsoil. The size of the drains needed to discharge the flow must be found from the program DRMULTI, using the inflow per metre given by the programs INCEP.

In homogeneous soil, a normal drain trench is wide enough in many cases. However, drains in a less permeable top layer require much wider trenches or broad ditches. A practical solution is to put more than one drain in such locations. As the hydrological circumstances are often complicated and little known, the programs can only give global guidelines. In practice, the problem is usually solved by trial and error – if a single drain is insufficient, more are added.

The theory can be found in Chapter 7 (more detail in Annex 21). Annex 23 provides details about the use of the programs and examples.

## References

- Bardají, J. 1998. Geomorfología, hidromorfismo y salinidad. *Master en Ingeniería de Regadíos, Drenaje, tomo III*. Madrid, CEDEX. 96 pp.
- Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A. & Holtslag, A.A.M. 1998a. A remote sensing Surface Energy Balance Algorithm for Land (SEBAL), part 1: formulation. *J. Hydrol.*, 212–213: 198–212.
- Bastiaanssen, W.G.M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J., Roerink, G.J. & Van der Wal, T. 1998b. The Surface Energy Balance Algorithm for Land (SEBAL), part 2: validation. *J. Hydrol.*, 212–213: 213–229.
- Boonstra, J. 1994. Estimating peak runoff rates. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 111–143. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Boonstra, J. & De Ridder, N.A. 1994. Single-well and aquifer tests. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 341–375. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Boumans, J.H. 1979. Drainage calculations in stratified soils using the anisotropic soil model to simulate hydraulic conductivity conditions. In J. Wesseling, ed. *Proceedings of the International Drainage Workshop*, pp. 108–123. ILRI Publication 25. Wageningen, The Netherlands, ILRI.
- Chieng, S. 1999. Use of geographic information systems and computer-aided design and drafting techniques for drainage planning and system design. In R.W. Skaggs & J. Van Schilfgaarde, eds. *Agricultural drainage*, pp. 893–908. Agronomy Series 38. Madison, USA.
- Childs, E.C. 1969. *The physical basis of soil water phenomena*. London, Wiley-Interscience.
- Chossat, J.C. & Saugnac, A.M. 1985. Relation entre conductivité hydraulique et porosité de drainage mesurées par la méthode du puits et des piezomètres. *Sci. du Sol*, 1985/3.
- Croon, F.W. & Risseuw, I.A. 2005. It is not always safe to save water; effects of water-saving irrigation methods on soil salinity control in (semi-)arid regions. *Proc. ICID Congress*. Beijing.
- De Ridder, N.A. 1994. Groundwater investigations. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 33–74. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- De Vries, W.S. & Huyskens, E.J. 1994. Gravity outlet structures. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 1001–1040. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Diwan, P.L. 1997. Control of drainable shallow groundwater through biological management options. *Proc. 7th International Drainage Workshop, Vol. 3*, p M12–1 to M12–12. Penang, Malaysia, ICID.
- Egyptian–Dutch Panel for Land Drainage. 1977–79. *Field research on water management of rice fields water. Advisory Panel project reports (1977, 1978 and 1979)*. Cairo, Drainage Research Institute, and Wageningen, The Netherlands, ILRI.
- FAO. 1974. *Effective rainfall*, by N.G. Dastane. FAO Irrigation and Drainage Paper No. 25. Rome. 68 pp.
- FAO. 1976. *Drainage testing*, by P.J. Dieleman & B.D. Traford. FAO Irrigation and Drainage Paper No. 28. Rome. 172 pp.
- FAO. 1977a. *Crop water requirements*, by J. Doorenbos & W.O. Pruitt. FAO Irrigation and Drainage Paper No. 24, revised edition (reprinted 1992). Rome. 144 pp.
- FAO. 1977b. *Irrigation canal lining*, by D.B. Kraatz. FAO Irrigation and Drainage Paper No. 2. Rome. 170 pp.

- FAO. 1980. *Drainage design factors*. FAO Irrigation and Drainage Paper No. 38. Rome. 52 pp.
- FAO. 1985. *Water quality for agriculture*, by R.S. Ayers & D.W. Westcot. FAO Irrigation and Drainage Paper No. 29 Rev. 1. Rome. 174 pp.
- FAO. 1992a. *Wastewater treatment and use in agriculture*, by M.B. Pescod. FAO Irrigation and Drainage Paper No. 47. Rome. 125 pp.
- FAO. 1992b. *The use of saline waters for crop production*, by J.D. Rhoades, A. Kandiah & A.M. Mashali. FAO Irrigation and Drainage Paper No. 48. Rome. 131 pp.
- FAO. 1995. *Guidelines for planning irrigation and drainage investment projects*. FAO Investment Centre Technical Paper No. 11. Rome. 188 pp.
- FAO. 1996. *Control of water pollution from agriculture*, by E.D. Ongley. FAO Irrigation and Drainage Paper No. 55. Rome. 101 pp.
- FAO. 1997. *Quality control of wastewater for irrigated crop production*, by D.W. Westcot. FAO Water Report No. 10. Rome. 86 pp.
- FAO. 1998. *Crop evapotranspiration – guidelines for computing crop water requirements*, by R.G. Allen, L.S. Pereira, D. Raes & M. Smith. FAO Irrigation and Drainage Paper No. 56. Rome. 300 pp.
- FAO. 1999. *Soil salinity assessment, methods and interpretation of electrical conductivity measurements*, by J.D. Rhoades, F. Chanduvi & S. Lesh. FAO Irrigation and Drainage Paper No. 57. Rome. 150 pp.
- FAO. 2002a. *Crops and drops: making the best use of water for agriculture*. Rome. 22 pp.
- FAO. 2002b. *Agricultural drainage water management in arid and semi-arid areas*, by K.K. Tanji & N.C. Kielen. FAO Irrigation and Drainage Paper No. 61. Rome. 188 pp.
- FAO. 2005. *Materials for subsurface land drainage systems*, by L.C.P.M. Stuyt, W. Diericks & J. Martínez Beltrán. FAO Irrigation and Drainage Paper No. 60 Rev. 1. Rome. 183 pp.
- FAO. 2006. Water desalination for agricultural applications. In J. Martínez Beltrán & S. Koo-Oshima, eds. *Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, 26–27 April 2004*. Land and Water Discussion Paper No. 5. Rome. 48 pp.
- FAO/ICID. 1997. *Management of agricultural drainage water quality*, by C.A. Madramootoo, W.R. Johnston & L.S. Willardson, eds. FAO Water Report No. 13. Rome. 94 pp.
- FAO/IPTRID. 2002. *Biodrainage; principles, experiences and applications*, by A.F. Heuperman, A.S. Kapoor & H.W. Denecke. Knowledge Synthesis Report No. 6. Rome. 79 pp.
- FAO/IPTRID. 2005. *Aral Sea basin initiative. Towards a strategy for sustainable irrigated agriculture with feasible investment in drainage*, by J.W. Kijne. Synthesis Report. Rome. 72 pp.
- FAO/ODA. 1995. *Environmental impact assessment of irrigation and drainage projects*, by T.C. Dougherty & A.W. Hall. FAO Irrigation and Drainage Paper No. 53. Rome. 74 pp.
- FAO/UNESCO. 1973. *Irrigation, drainage and salinity. An international source book*, by V.A. Kovda, C. Van der Berg & R.M. Hagan, eds. London, Hutchinson/FAO/UNESCO. 510 pp.
- Gowing, J.W. & Wyseure, G.C.L. 1992. Dry drainage: a sustainable and cost effective solution to waterlogging and salinisation. *Proceedings of ICID's 5th International Drainage Workshop*, pp. 6–26 to 6–34. Lahore, Pakistan.
- ICID. 1993. *The ICID environmental check-list*. Oxfordshire, United Kingdom, H.R. Wallingford. 130 pp.
- ILRI. 1994. *Drainage principles and applications*, by H.P. Ritzema, ed. 2nd edition. Publication 16. Wageningen, The Netherlands. 1125 pp.
- ILRI. 2005. *SAHYSMOD, spatial agro-hydro-salinity model*. Version 1.7. Description of principles, user manual and case studies. SAHYSMOD working group of ILRI. Wageningen, The Netherlands. 134 pp.
- IRYDA. 1989a. *Evaluación de tierras para regadío de la Zona Regable del Muga, Gerona*. Madrid.
- IRYDA. 1989b. *Informe previo del anteproyecto de drenaje del Sector IV de la Zona Regable del Muga, Gerona*. Madrid.

- Khouri, N., Kalbermattern, J.M. & Bartone, C.R.** 1994. *Re-use of wastewater in agriculture: a guide for planners*. Water and Sanitation Report 6. Washington DC, UNDP-World Bank Water and Sanitation Program, World Bank. 49 pp.
- Kruseman, G.P. & De Ridder, N.A.** 1994. *Analysis and evaluation of pumping tests data*. ILRI Publication 47, 2nd. Wageningen, The Netherlands, ILRI. 377 pp.
- Maas, E.V. & Grattan, S.R.** 1999. Crop yields as affected by salinity. In R.W. Skaggs & J. Van Schilfhaarde, eds. *Agricultural drainage*. Agronomy Series 38. Madison, USA.
- Madramootoo, C.A.** 1999. Planning and design of drainage systems. In R.W. Skaggs & J. Van Schilfhaarde, eds. *Agricultural drainage*, pp. 871–892. Agronomy Series 38. Madison, USA.
- Martínez Beltrán, J.** 1978. *Drainage and reclamation of salt affected soils in the Bardenas area, Spain*. ILRI Publication 24. Wageningen, The Netherlands, ILRI. 321 pp.
- Martínez Beltrán, J.** 1993. Soil survey and land evaluation for planning, design and management of irrigation districts. In: *Cahiers Options Méditerranéennes, volume 1, n° 2*. Soils in the Mediterranean Region: use, management and future trends, pp. 179–194. Zaragoza, Spain, CIHEAM.
- Martínez Beltrán, J.** 1999. Land drainage. In H.N. van Lier, L.S. Pereira & F.R. Steiner, eds. *Land and water engineering, Volume 1, CIGR Handbook of Agricultural Engineering*. pp. 430–484. Edited by CIGR-The International Commission of Agricultural Engineering. St. Joseph, USA, ASAE.
- Meinardi, C.R.** 1974. De chemische samenstelling van het grondwater van de Veluwe. *R.I.D.-Meded.*, 74: 4.
- Nijland, H.J., Croon, F.W. & Ritzema, H.P.** 2005. *Subsurface drainage practices: guidelines for the implementation, operation and maintenance of subsurface pipe drainage systems*. Alterra-ILRI Publication No. 60. Wageningen, The Netherlands. pp. 608.
- Natural Resources Conservation Service (NRCS)**. National Water and Climate Center, US Department of Agriculture, USA (available at [www.wcc.nrcs.usda.gov](http://www.wcc.nrcs.usda.gov)).
- Ochs, W.J. & Bishay, B.G.** 1992. *Drainage guidelines*. World Bank Technical Paper No. 195. Washington, DC. 186 pp.
- Oosterbaan, R.J.** 1994. Frequency and regression analysis. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 175–223. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Pulido Madrigal, L., López de Santa Ana, J.L., Cisneros Estrada, O.X. & Robles Rubio, B.** 2000. Estimación de cosechas por medio de imágenes de satélite en el Distrito de Riego 075 Río Fuerte, Sinaloa. *Memorias de la XI Reunión Nacional SELPER-México*. Sociedad de Especialistas Latinoamericanos de Percepción Remota y Sistemas de Información Espacial, Cuernavaca, México.
- Pulido Madrigal, L., Robles Rubio, B.D., González Meraz, J. & Cisneros Estrada, O.X.** 2003a. *Manual para identificación de salinidad del suelo y cartografía del rendimiento de cultivos con sensores remotos*. Jiutepec, Morelos, México, IMTA, Coordinación de Tecnología de Riego y Drenaje. 96 pp.
- Pulido Madrigal, L., Wiegand, C.L., González Meraz, J., Robles Rubio, B.D., Cisneros Estrada, O.X. & Lemus, R.O.** 2003b. La salinidad del suelo y su efecto en el rendimiento de los cultivos estudiados con imágenes de satélite en tres distritos de riego. *Ing. Hidr. Méx.*, 18(2): 83–97.
- Pulido Madrigal, L., López de Santa Ana, J.L., González Meraz, J., Cisneros Estrada, O.X. & Robles Rubio, B.** 1999. Aplicación de imágenes de satélite, inducción electromagnética y sistemas de información geográfica para estudiar la salinidad del suelo, el drenaje y el rendimiento en el Distrito de Riego 075 Río Fuerte, Sinaloa. *Memorias del IX Congreso Nacional de Especialistas en Irrigación*, pp. 129–136. Culiacán, México.
- Raadsmas, S. & Schulze, F.E.** 1974. Surface field drainage systems. In: *ILRI Publication 16, Vol. IV*. pp. 67–121. Wageningen, The Netherlands, ILRI.
- Raudkivi, A.J. & Callander, R.A.** 1976. *Analysis of groundwater flow*. London, Arnold.
- Risseuw, I.A.** 1976. *La producción de caña de azúcar en función del régimen freático*. Unpublished report, Dutch Mission, ICIA-CECOAAP, Casa Grande, Peru.

- Sevenhuijsen, R.J.** 1994. Surface drainage systems. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 799–826. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Sieben, W.H.** 1964. *Relation between drainage conditions and crop yield for young light clay soils in the Noordoostpolder*. Zwolle, The Netherlands, Rijksdienst voor de Ijsselmeerpolders/Tjeenk Willink.
- Sieben, W.H.** 1965. Het verband tussen outwatering en opbrengst bij de jonge zavelgronden in de Noordoostpolder. *Van Zee tot Land* 40: 1–117.
- Skaggs, R.W.** 1999. Drainage simulation models. In R.W. Skaggs & J. Van Schilfgaarde, eds. *Agricultural drainage*, pp. 469–500. Agronomy Series 38. Madison, USA.
- Skaggs, R.W. & Chescheir, G.M.** 1999. Application of drainage simulation models. In R.W. Skaggs & J. Van Schilfgaarde, eds. *Agricultural drainage*, pp. 537–564. Agronomy Series 38. Madison, USA.
- Skaggs, R.W. & Van Schilfgaarde, J., eds.** 1999. *Agricultural drainage*. Agronomy Series 38. Madison, USA. 1328 pp.
- Smedema, L.K.** 2002. Land drainage, an instrument for agricultural and rural development. *Proceedings of the 18th ICID Congress, Special Event on World Vision for Water for Food and Rural Development*, Montreal 2002. New Delhi, ICID.
- Smedema, L.K. & Ochs, W.J.** 1998. Impediments to improved drainage in developing countries. *Proceedings of the ASAE 7th International Drainage Symposium*. pp. 285–292. St. Joseph, USA.
- Smedema, L.K. & Shiati, K.** 2002. Irrigation and salinity: a perspective review of the salinity hazards of irrigation development in the arid zone. *Irri. & Drain. Sys.*, 16: 161–174.
- Smedema, L.K., Vlotman, W.F. & Rycroft, D.W.** 2004. *Modern land drainage. Planning, design and management of agricultural drainage systems*. Leiden, The Netherlands, A.A. Balkema Publishers, Taylor&Francis. 446 pp.
- STOWA.** 2000. DUFLOW for Windows. Utrecht, The Netherlands, Stichting Toegepast Waterbeheer (available at [www.stowa.nl](http://www.stowa.nl)).
- UNEP/WHO.** 1996. *A practical guide to the design and implementation of freshwater quality studies and monitoring programmes*, by J. Bartram & R. Ballance, eds. Geneva, Switzerland.
- US Army Corps of Engineers (USACE).** 1990. *HEC-1 and HEC-2 packages*. Davis, USA.
- USBR.** 1984. *Drainage manual*. A Water Resources Tech. Publication. Second printing. Denver, USA, US Dept. of Interior, Bureau of Reclamation. 286 pp.
- Van Aart, R. & Van Alphen, J.G.** 1994. Procedures in drainage surveys. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 691–724. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- Van Dam, J.C., Huygen, J., Wesseling, J.G., Feddes, R.A., Kabat, P., van Walsum, P.E.V., Groenendijk, P. & van Diepen, C.A.** 1997. *Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment*. Report 71. Wageningen, The Netherlands, Department of Water Resources, Wageningen Agricultural University. Technical Document 45. Wageningen, The Netherlands, DLO Winand Staring Centre.
- Vázquez Guzmán, A.** 1999. *Saneamiento y drenaje, construcción y mecanización*. Madrid, Editorial Agrícola Española. 151 pp.
- Veenbos, J.S.** 1972. *Soil survey*. Lecture notes of the MSc. Course on Soil and Water Management. Agricultural University, Wageningen, The Netherlands.
- Vlotman, W.F., Willardson, L.S. & Dierickx, W.** 2000. *Envelope design for subsurface drains*. Publication 56. Wageningen, The Netherlands, ILRI. 358 pp.
- Wanielista, M.** 1978. *Storm water management, quantity and quality*. Michigan, USA, Ann Arbor Science.
- Wesseling, J. & Kruseman, G.P.** 1974. Deriving aquifer characteristics from pumping tests. In: *Drainage Principles and Applications*, pp. 297–328. ILRI Publication 16, Vol. III Surveys and Investigations. Wageningen, The Netherlands, ILRI.

- Wiegand, C.L.** 2000. *Use of remote sensing for salinity assessment*. Unpublished technical document prepared for the Land and Water Development Division of FAO.
- Wijdieks, J. & Bos, M.G.** 1994. Pumps and pumping stations. In H.P. Ritzema, ed. *Drainage principles and applications*, pp. 965–998. 2nd edition. ILRI Publication 16. Wageningen, The Netherlands, ILRI.
- World Bank.** 1991. *The economics of project analysis - a practitioner's guide*. Washington, DC., EDI – World Bank. 318 pp.
- World Bank.** 2004. *Reclaiming drainage, toward an integrated approach*, by S. Abdel-Dayam, J. Hoevenaars, P.P. Mollinga, W. Scheumann, R. Sootweg & F. van Steenberg. Agriculture and Rural Development Report 1. Washington, DC.
- World Meteorological Organization (WMO).** 1974. *Guide to hydrological practices*. 3rd edition. Technical Publication No. 168. Geneva, Switzerland.