Water Requirements for Irrigation and the Environment

The authors can be reached at the following address:

International Institute for
Geo-Information Science and Earth
Observation, ITC
P.O.Box 6, 7500 AA Enschede
The Netherlands
marinusgbos@cs.com
www.bos-water.nl

Alterra, Wageningen UR
Droevendaalsesteeg 3, 6708 BP
Wageningen, The Netherlands
rob.kselik@wur.nl

University of Idaho
Research and Extension Center
Kimberly, U.S.A
rallen@kimberly.uidaho.edu

International Water Management
Institute, IWMI
P.O.Box 2075, Colombo,
Sri Lanka
d.molden@cgiar.org
www.iwmi.cgiar.org

Previous versions of CRIWAR:

Version 1.*	Bos, M.G. 1988, Crop irrigation water requirements, ILRI, Wageningen (limited distribution)
Version 2.*	Bos M.G., J. Vos, and R.A. Feddes. 1996. CRIWAR 2.0: A Simulation Model on Crop Irrigation Water Requirements. ILRI, Wageningen

Marinus G. Bos • Rob A.L. Kselik
Richard G. Allen • David J. Molden

Water Requirements for Irrigation and the Environment

Springer

Marinus G. Bos
International Institute for Geo-Information
Science and Earth Observation
ITC

Richard G. Allen
University of Idaho
Research and Extension Center

Rob A.L. Kselik
International Institute for Land Reclamation
and Improvement
Alterra-ILRI

David J. Molden
International Water Management Institute
IWMI

ISBN: 978-1-4020-8947-3 e-ISBN: 978-1-4020-8948-0

Library of Congress Control Number: 2008933942

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Abstract M.G. Bos, R.A.L. Kselik, R.G. Allen and D.J. Molden 2008. *Water Requirements for Irrigation and the Environment*. Springer, Dordrecht, ISBN 978-1-4020-8947-3

Irrigated agriculture produces about 40% of all food and fibre on about 16% of all cropped land. As such, irrigated agriculture is a productive user of resources; both in terms of yield per cropped area and in yield per volume of water consumed. Many irrigation projects, however, use (divert or withdraw) much more water than consumed by the crop. The non-consumed fraction of the water causes a variety of undesirable effects ranging from water-logging and salinity within the irrigated area to downstream water pollution.

This book discusses all components of the water balance of an irrigated area; evapotranspiration (Chapter 2), effective precipitation (Chapter 3) and capillary rise from the groundwater table (Chapter 4). Chapter 5 then combines all components into a water management strategy that balances actual evapotranspiration (and thus crop yield) with the groundwater balance of the irrigated area (for a sustainable environment). Chapter 6 presents CRIWAR 3.0, being a simulation program which transfers the estimated evapotranspiration of the cropped area into the water requirements of an irrigated area.

The computer program presented in this publication can accommodate a wide variety of cropping patterns as well as many different input and output units. This version greatly expands upon the capabilities of previously published programs.

Keywords Water management; irrigation; groundwater; drainage; environment; water balance; crop production.

Preface

Each day, the continuing growth of world population places new demands on our water resources. More water is needed for all the processes of life: food production, municipal supply, industrial water use, power generation, navigation, recreation, etc. At the same time, environmental water needs are increasingly being recognized, limiting the sources of new water and further increasing the competition for available supplies.

Improved management of our water resources is needed to ensure the equitable distribution of water to competing users. There are especially significant opportunities for conservation and more effective water use by the world's largest user: agriculture. Accurate delivery of the necessary amounts of water at the correct times can both conserve water and improve the quantity and quality of agricultural products. Thus, the method to quantify the irrigation water requirement described in this manual has a key role to play as we address the future water, food, and fibre needs of our world.

This manual gives additional information on capillary rise as a source of water and on the method by which groundwater table management can be used to reduce the surface water requirement during the peak season. This groundwater table management also reduces the need for artificial drainage and thus reduces the negative effect of drainage effluent on the downstream ecosystem.

In addition, the CRIWAR software can be a helpful tool in the management of operational irrigation projects with frequent changing cropping patterns and in the performance assessment of irrigation and drainage.

The range of potential applications for this book and related software is unlimited. We hope that this book will contribute to the effective management of one of the earth's most widely needed, used, and visible natural resources: water.

Marinus G. Bos, Enschede, The Netherlands
Rob A.L. Kselik, Wageningen, The Netherlands
Richard G. Allen, Kimberly, Idaho, USA
David J. Molden, Colombo, Sri Lanka

Contents

List of Symbols

C	height of capillary rise (m)
C_d	denominator constant that changes with reference type and calculation time step (s m^{-1})
C_n	numerator constant that changes with reference type and calculation time step (K mm s^3 Mg^{-1} day^{-1} or K mm s^3 Mg^{-1} h^{-1})
c	dimensionless adjustment factor
c_p	specific heat of dry air at constant pressure (J/kg K)
D_M	day of the month (1–31)
$D_{e,j-1}$	cumulative depletion from the soil surface layer at the end of day j - 1 (the previous day in mm)
d_r	inverse relative distance factor (squared) for the earth-sun (dimensionless)
DF	depleted fraction (dimensionless)
$DP_{ei,\,j}$	deep percolation in mm from the f_{ew} fraction of the soil surface layer on day j if soil water content exceeds field capacity
E_a	isothermal evaporation rate (kg/m^2 s)
E_j	evaporation in mm on day j (i.e., $E_j = K_e\ ET_0$)
E_0	open water evaporation rate (kg/m^2 s)
e_a	mean actual vapor pressure at 1.5–2.5 m height (kPa), Δ is slope of the saturation vapor pressure versus temperature curve (kPa °C^{-1})
e^o	saturation vapor pressure function
e_s	saturation vapor pressure at 1.5–2.5 m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature
e_z	prevailing vapour pressure in the external air, measured at the same height as T_z (k/Pa)
ET_0	standardized reference ET for a 12 cm tall, cool season grass in mm day^{-1} for daily time steps or mm h^{-1} for hourly time steps
ET_a	actual evapotranspiration (mm/day)

$ET_{a,gross}$	sum of the actual evapotranspiration from the (irrigated) cropped area and all fallow (non-cropped) area within the command area served by the irrigation system
$ET_{a,non.ir}$	actual evapotranspiration from all fallow (non-irrigated) area within the command area
ET_L	target landscape ET (in mm day^{-1}, mm $month^{-1}$, or mm $year^{-1}$)
ET_p	potential; evapotranspiration (mm/day)
F	actual retention (mm)
F↓	downward force (N)
f	correction factor which depends on the depth of the irrigation water application per turn (dimensionless)
$f_{cd\ \beta > 0.3}$	cloudiness function for the time period prior to when β falls below 0.3 radians during afternoon or evening (dimensionless)
f_{cd}	cloudiness function [dimensionless] and limited to $0.05 \le f_{cd} \le 1.0$
f_{ew}	fraction of the soil that is both exposed to solar radiation and that is wetted
f(u)	wind function; $f(u) = 1 + 0.864u_2$
G	soil heat flux density at the soil surface in MJ m^{-2} day^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps
G_{day}	daily (24-h) soil heat flux density (MJ m^{-2} day^{-1})
G_{sc}	solar constant (4.92 MJ m^{-2} h^{-1})
g	acceleration due to gravity ($g = 9.81\ m/s^2$)
H	flux density of sensible heat into the air (W/m^2)
h	(hydraulic) head (m)
I_a	initial abstraction (mm)
I_j	irrigation depth in mm on day j that infiltrates the soil
J	number of the day in the year between 1 (1 January) and 365 or 366 (31 December)
K	hydraulic conductivity as a function of h (m/day)
K_c	crop coefficient
K_{cb}	basal crop coefficient [between 0 to 1.4]
K_e	soil water evaporation coefficient [between 0 to 1.4]
K_r	evaporation reduction coefficient
L_z	longitude of the center of the local time zone (expressed as positive degrees west of Greenwich, England)
M	number of the month (1–12)
NDVI	Normalized Difference Vegetation Index
P	total precipitation (mm/day or mm/month)
P_j	precipitation in mm on the soil surface on day j
P_e	effective precipitation (mm/day or mm/month)
p_a	atmospheric pressure (kPa)

r_a aerodynamic diffusion resistance, assumed to be the same for heat and water vapour (s/m)
R_n calculated net radiation at the crop surface in MJ m^{-2} day^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps
R_{ns} net short-wave radiation, (MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1})
R_{nl} net outgoing long-wave radiation, (MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1})
R_s incoming solar radiation (MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1})
T mean daily or hourly air temperature at 1.5–2.5 m height (°C)
T_{av} daily average air temperature (°C); $T_{av} = (T_{max} + T_{min})/2$
$T_{ei,\,j}$ day j
T_{min} minimum air temperature, °C
T_{max} maximum air temperature, °C
$T_{K\,min}$ minimum absolute temperature during the 24-hour period (K). K = °C + 273.15
$T_{K\,max}$ maximum absolute temperature during the 24-hour period (K)
$T_{K\,hr}$ mean absolute temperature during the hourly period (K)
T_p statistical value (dimensionless)
T_s temperature at the evaporating (water) surface (°C)
T_z air temperature at a height z above the surface (°C)
t standard clock time at the midpoint of the period in h (after correcting time for any daylight savings shift)
TD difference between mean daily maximum and minimum temperature (°C); $TD = (T_{max} - T_{min})$
TEW total evaporable water (mm)
Y number of the year (for example 1996 or 96)
R_A extraterrestrial radiation (MJ/m^2 per day) or (MJ m^{-2} h^{-1})
REW readily evaporable water (mm)
RO_j runoff in mm from the soil surface on day j
R_a field application ratio (dimensionless)
S maximum potential difference between precipitation and runoff beginning at the time precipitation starts (also named maximum retention) (mm)
Q accumulated runoff depth (mm)
P accumulated precipitation depth (mm)
p pressure energy per unit of volume (Pa)
q vertical flow rate per unit area (m/day)
s standard deviation
u_2 wind speed at 2.0 m above ground surface (m/s)
V_c total volume of surface water diverted from the water source (river, reservoir) into the irrigation system
V_d total volume of irrigation water supplied to the inlets of the distribution system

V_f	volume of irrigation water delivered to the fields during the period under consideration (m^3/period)
V_{grw}	total volume of groundwater pumped into the conveyance system
V_m	volume of irrigation water needed, and made available, to avoid undesirable stress in the crops throughout the growing cycle (m^3/period)
$V_{non\text{-}ir}$	total volume of water supplied for non-irrigation purposes. In most irrigation systems this volume is negligible with respect to V_d
Z_e	effective depth of the surface soil subject to drying to 0.5 θ_{WP} by way of evaporation (m)
z	elevation head, being positive in the upward direction (m)
z	station elevation above sea level (m)
α	albedo, fixed at 0.23 for both daily and hourly time steps for reference ET (dimensionless)
β	angle of the sun above the horizon (radians)
γ	psychrometric constant (kPa °C^{-1})
Δ	slope of the saturation vapor pressure versus temperature curve (kPa °C^{-1})
δ	solar declination (radians)
ε	ratio of molecular masses of water vapour over dry air (dimensionless)
θ_{FC}	soil moisture at field capacity (m^3 m^{-3})
θ_{WP}	soil moisture at wilting point (m^3 m^{-3})
λ	latent heat of vaporization (J/kg)
λE	flux density of latent heat into the air (W/m^2)
ρ	density of water (ρ = 1,000 kg/m^3)
ρ_a	density of moist air (kg/m^3)
σ	Stefan-Boltzmann constant (4.901×10^{-9} MJ K^{-4} m^{-2} day^{-1} and 2.042×10^{-10} MJ K^{-4} m^{-2} h^{-1})
φ	station latitude (radians)
ω_1	solar time angle at beginning of period (radians)
ω_2	solar time angle at end of period (radians)
ω_s	sunset hour angle (radians)

Chapter 1
Introduction

1.1 Growth of Vegetation

For vegetation to grow, it should transpire sufficient water through the stomata on its leaves. This water is taken from the soil via the roots. The part of the soil from which the roots take water is named the effective root zone (Fig. 1.1). Water also moves into the atmosphere through evaporation from plant surfaces (following precipitation or irrigation) and from the bare soil surface in between the vegetation.[1] Part of the water that evaporates from the bare soil surface originates from precipitation or irrigation. The remaining part rises through capillary action from the groundwater table to the soil surface. The sum of the evaporation and transpiration is known as *EvapoTranspiration* (*ET*). If sufficient water is available to meet the sum of evaporation and transpiration, the *ET* will reach its (maximum) potential value, ET_p. Otherwise, the actual evapotranspiration (ET_a) will be less than ET_p (see Chapters 4 and 5).

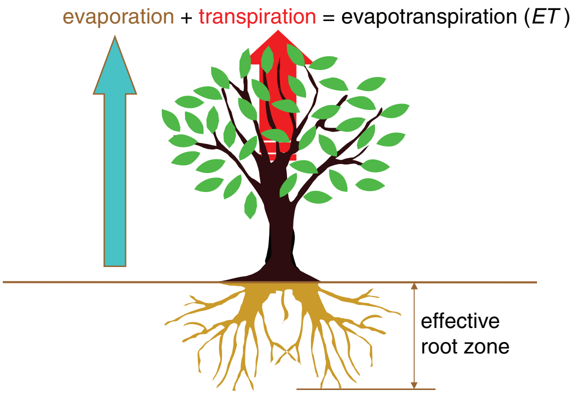

Fig. 1.1 Terminology

[1] Water evaporating directly from the groundwater surface is ignored in this context (also see Chapter 4).

The potential evapotranspiration, ET_p, is the volume of water required to meet the crop's potential evapotranspiration over the whole growing season, under a given cropping pattern and in a specific climate.

Figure 1.2 shows the mondial distribution of average annual values of the relative evapo-transpiration (ET_a/ET_p). Traditionally, the main areas of food production have been areas with relatively fertile soils, a sufficient supply of water, and favourable climatic conditions. The qualification 'sufficient supply of water' can be re-phrased as: rain-fed agriculture traditionally is practised in areas where the average annual value of ET_a/ET_p is greater than about 0.8, otherwise irrigation was introduced. For some decades, irrigation has also been used as a form of 'insurance' on yield reductions due to dry spells and to control the uniform quality of high value (export) crops.

Because of the increasing demand for agricultural products by a rapidly growing world population, agriculture has expanded horizontally into areas where conditions for production are less favourable. It has also expanded vertically by increasing production per unit area of land through intensification. As a result of this horizontal and vertical expansion, agricultural production has increased considerably. Food and fibres presently are grown on about 1,500 million hectares rain-fed land and 250 million hectares irrigated land. However, the latter 14% of the agricultural area produces 40% of all crops. Hence, irrigation plays a major role in feeding the world.

To meet the growing demand for food and fibre, crop production should increase. However, from a land and water use perspective there are two major constraints:

– ***LAND*** is the traditional constraint. If more crops were needed, more land was reclaimed while the goal was to maximise yield in terms of kg/ha. However, for the last four decades, most suitable areas have already been cropped while urban development infringes on agricultural areas.
– ***WATER*** is the ever more important constraint. Already for 10% of world population (in arid and semi-arid countries) the annually available volume of water

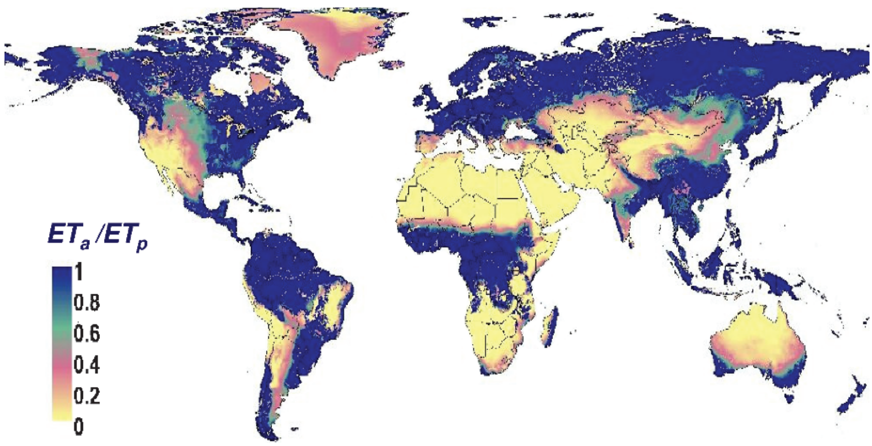

Fig. 1.2 Average annual distribution of the relative evapotranspiration (Adapted from Droogers et al. 2001)

dropped below the critical level of 1,700 m^3 per capita (Fig. 1.3). In such areas, the crop yield in terms of kg/m^3 water becomes increasingly important. Also the quality of water (reuse and disposal) is due to become increasingly important. However, more alarming is that the next group in Fig. 1.3, being 49% of world population, that will pass the water scarcity limit before 2025.

The future challenge is to grow sufficient food on current agricultural land; thus without undue infringement on nature. This should be done in such a way that water use does not damage the environment. Hence, the water balance within the agricultural area should remain stable. To meet this challenge, we follow two tracks which merge into a water use strategy:

Crop production track

This track starts with an estimate of the crop water requirements in order to produce food (and fibre). It then estimates the additional water required to operate an irrigation system. Combining these requirements yields the irrigation water demand of the irrigated area.

Water balance track

This track considers the three major components of the water balance of an irrigated area: actual ET, precipitation, and actual irrigation water supply. These components are matched in such a way that the groundwater table in the area remains stable.

↓ ↓

Water use strategy

Merging the irrigation water demand and the actual (planned) irrigation water supply, results in a water use strategy that allows the production of a crop within a stable environment.

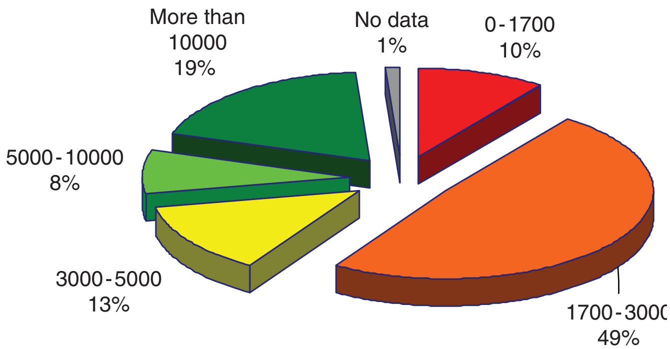

Fig. 1.3 Distribution of world population among economies grouped by annual freshwater resources in cubic metre per capita (World Bank 1999)

1.2 Crop Growth and Evapotranspiration

As mentioned above, the crop transpires water during its growth. With respect to crop water requirement we distinguish four different stages of crop development that are considered for field and vegetable crops (Fig. 1.4):

- The initial growth stage being the germination and early growth stage of the crop. During this stage, the soil surface is not, or is hardly, covered by the crop canopy (ground cover less than 10%). Although transpiration stress can be very harmful during this stage, most water will evaporate from the soil. Hence, during this stage the crop type has little effect on the ET_{p}-value.
- Crop development stage: lasting from the end of the initial stage until the attainment of effective full ground cover (between 70% and 80%). Please note that this does not mean that the crop has reached its matured height.
- Mid-season stage: lasting from the attainment of effective full ground cover to the start of maturing of the crop. Maturing of the crop may be indicated by leaves discolouring (beans) or leaves falling off (cotton). For some crops, this stage may last until very near harvest (sugar beet) unless irrigation is omitted at late season and a reduction in ET_p is induced to increase yield and/or quality (sugarcane, cotton, some grains). Normally this stage lasts well past the flowering stage of annual crops.
- Late season stage: lasting from the end of the mid-season stage until full maturity or harvest of the crop.

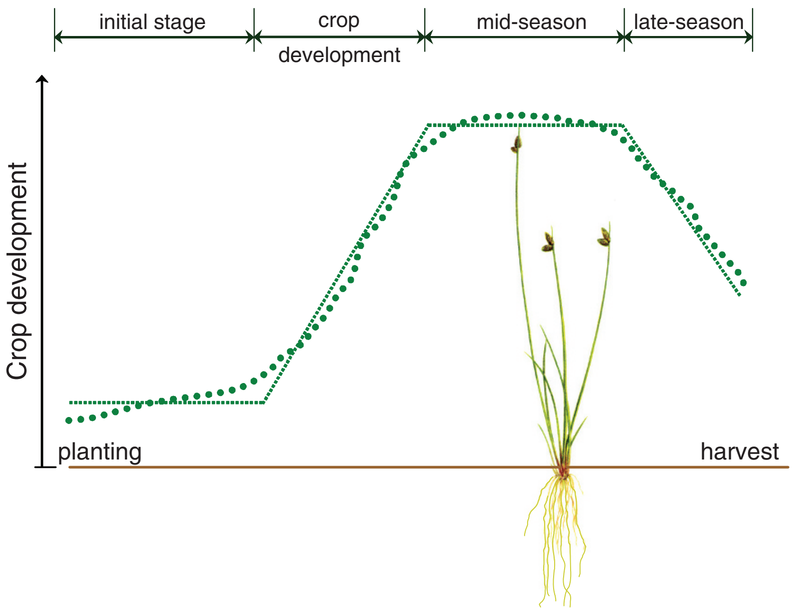

Fig. 1.4 Actual crop development and four schematised growth stages

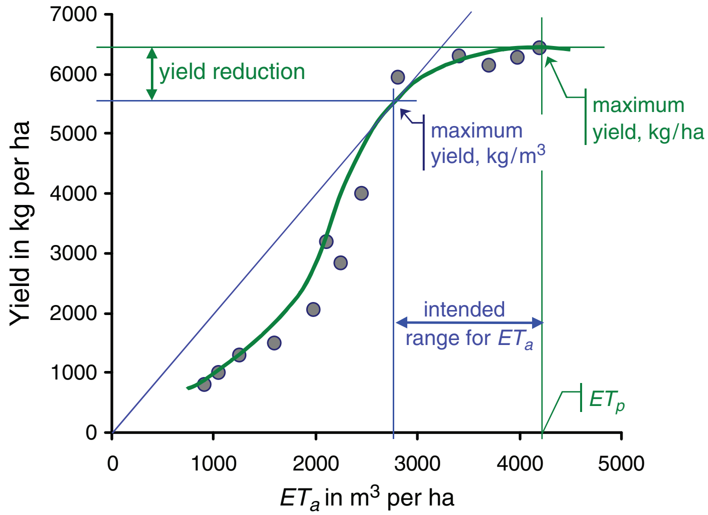

Fig. 1.5 Crop production function showing the cumulative ET_a versus yield for wheat, Central Great Plains, USA (Data points from Hanks et al. 1967)

During each growth stage the ET_a will be equal to ET_p if the crop is not water stressed. The yield of the crop then is maximized in terms of kg/ha as illustrated in the crop production function of Fig. 1.5. Normally, however, the crop will feel some water stress resulting in a lower cumulative ET_a and a lower yield. Depending on the width of the upper (mid-season) part of the crop production function, the ratio ET_a/ET_p can be reduced considerably while crop yield remains high. In the wheat example of Fig. 1.5, the ratio ET_a/ET_p may decrease to 0.67 (being 2,800/4,200) while yield in terms of kg/ha only decreases to 0.87 (being 5,600/6,400) of potential yield. In fact, with this decrease in ET_a the productivity in terms of kg/m^3 will become maximum, which should be the operational target if water is the limiting resource (Bos 1980). For the wheat example of Fig. 1.5, the intended value of ET_a/ET_p should thus be greater than 0.67.

1.3 The Water Balance of an Area

The water balance of a gross command (irrigation) area shows three sources of water: precipitation, groundwater inflow and river (surface) water diversion (Fig. 1.6). Part of all this water evapo-transpires from irrigated crops (fields) and partially from fallow land. This gross evapotranspiration is denoted as:

$$ET_{a,gross} = ET_a + ET_{a,non.ir} \qquad 1.1$$

Where:

$ET_{a,gross}$ = The sum of the actual evapotranspiration from the (irrigated) cropped area and all fallow (non-cropped) area within the command area served by the irrigation system

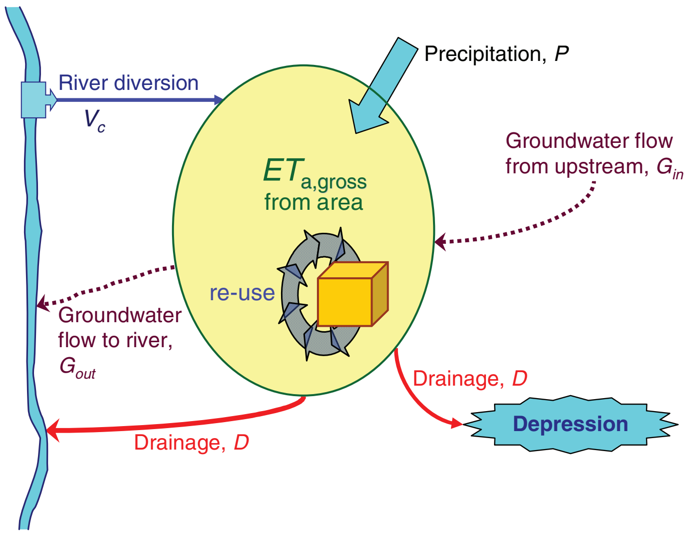

Fig. 1.6 The water balance of a gross command) area with irrigation

ET_a = The actual evapotranspiration from the cropped area within the irrigable area
$ET_{a,non.ir}$ = The actual evapotranspiration from all fallow (non-irrigated) area within the command area

Part of the command area will be permanently non-irrigated (land along canals, roads, villages, etc.). This part often ranges between 5% and 10% of the gross command area. The $ET_{a,non.ir}$ from this area depends on the ground cover (e.g. trees, grass, asphalt, houses). The remainder of the non-irrigated area consists of fields being fallow in between harvest and seeding/planting. For this part we assume that $ET_{a,non.ir}$ equals the evapotranspiration during the initial growth stage (see Section 1.2).

The part of the available water that does not evaporate will flow to downstream areas either via surface streams (drains) or as groundwater. If the summed inflow exceeds the outflow, part of the water will be stored within the irrigated area. This increased storage may cause water logging and salinity. If, on the other hand, the summed outflow exceeds the inflow, the groundwater table will drop. In first instance this will reduce the availability of capillary water to crop growth. With continued mining of groundwater, this water resource will be depleted. To avoid the above problems it is recommended to manage irrigation water (V_c) in such a way that the groundwater table remains stable from year to year.

To avoid the accumulation of salts (in the root zone of the crops) within the irrigated area of Fig. 1.6, about 10–20% (say 15%) of the total inflow ($V_c + P + G_{in}$) should discharge from the area as drainage (D) plus groundwater outflow (G_{out}). In other words; $ET_{a,gross}$ should be less than about 85% of the available water (inflow). Thus, for sustainability: