CRC FOR CATCHMENT HYDROLOGY
CSIRO LAND AND WATER
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ON-FARM AND COMMUNITY-SCALE SALT DISPOSAL BASINS ON THE RIVERINE PLAIN

BASINMAN - A WATER BALANCE MODEL FOR FARMS WITH SUBSURFACE PIPE DRAINAGE AND AN ON-FARM BASIN

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Summary

This report documents the development, testing and use of a water balance model (BASINMAN) for farms with subsurface pipe drainage and an on-farm evaporation basin. Previous studies of evaporation basins have tended to concentrate on the basin processes whilst ignoring the linkages to the drainage system and the farmed area.

The BASINMAN model was developed with the aim of increasing our understanding of the hydraulic relationships between the farmed area and basin system. From this we aimed to better optimise the design of on-farm basins to minimise the basin area whilst controlling waterlogging. The model is intended to assist with developing best management and design practices for on-farm evaporation basins and the subsurface drainage system.

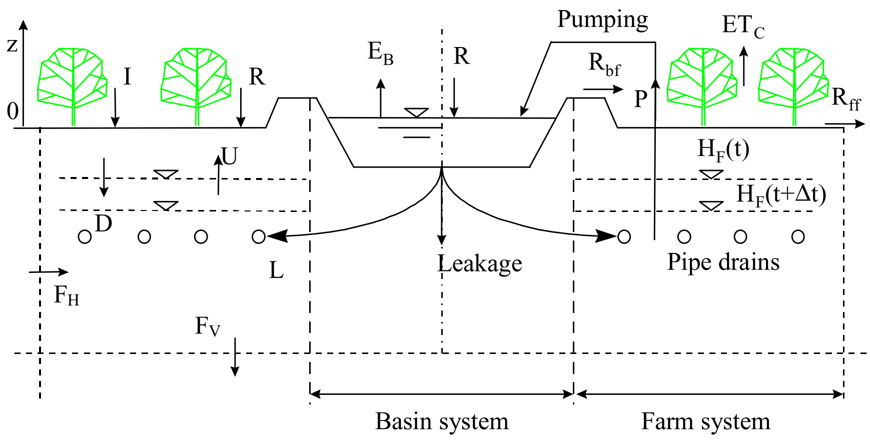
The model was developed to:

§ represent a single on-farm basin with associated farmland

§ simulate horizontal pipe drainage as found in most horticultural planting's in the Murray Darling basin

§ represent the system with easily available data and the outputs from the model should aid in optimising basin area against the key limiting factors

The following figure shows the conceptual diagram for the model. At this stage solute transport is not included in the model.



Conceptual diagram of on-farm evaporation basin system

Analytical solutions for the system processes have been applied where required. The system processes include:

§ irrigation - by crop water deficit or soil water deficit

§ recharge - using a simple tipping bucket (the model is two layered saturated and unsaturated)

§ drainage - using Houghoudt drainage theory

§ upflow - function developed by W. Meyer (CSIRO Land and Water, Adelaide)

§ crop water use - by reference evaporation and crop factors

§ basin leakage – fixed infiltration rate or Green-Ampt model

§ basin evaporation - open water or soil

§ interchange between basin and farm - Darcy flow

§ horizontal groundwater inflow – fixed net inflow rate applied

§ vertical groundwater leakage – fixed net down flow rate applied

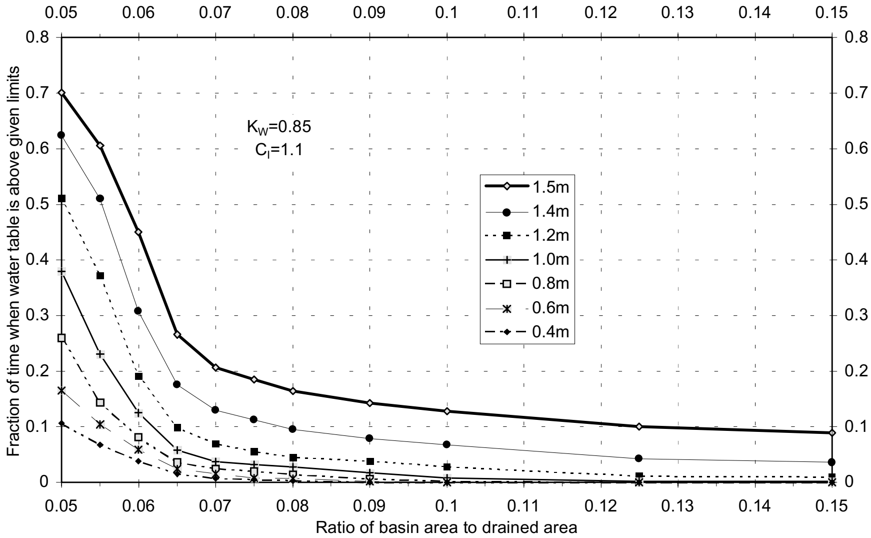
By simulating these processes, the model can represent a diverse range of hydraulic states both in the farmland and basin, as found in reality. This allows for the farmland to be either saturated or unsaturated and for the basin to function in 3 possible states: ponded/soil saturated, dry/soil unsaturated, ponded/soil unsaturated. The hydraulic state responds dynamically to the temporal variation of water fluxes in the linked farm/basin system.

The model was tested against measured field data for a newly commissioned on-farm basin in the Murrumbidgee Irrigation Area. The model was able to simulate the rapidly changing hydrological conditions in the farm and basin. The model was able to reasonably predict fluxes from the basin to the farmland and leakage through the basin. Also the irrigation regime was in good agreement with reality. The modelling of the farm water tables was not as representative of the actual conditions. This was probably due to the difficulty in determining an average farm water table height in the field.

The crop water use, recharge, water table conditions and subsurface drainage functions of the BASINMAN model were also compared against the SWAGMAN Destiny model developed at CSIRO Land and Water, Griffith. The two models were in relatively good agreement, although the Destiny model applied more irrigation water because the BASINMAN model delays irrigation if there is any rain on the scheduled irrigation day.

The model was used to test the sensitivity of the system to various factors. It was found that the inputs and outputs to the system such as irrigation, rainfall and evaporation created the largest changes. Internal factors such as soil type and basin leakage were relatively unimportant in a closed boundary system.

Multiple sets of basin areas were run on a daily time step using 35 years of weather records. The output daily water table height was then analysed to determine the proportion of time when the water table was above a set of given limits. This data represented graphically as in the figure below can be used to aid in selecting a minimum basin area whilst containing waterlogging to a tolerable level. The legend refers to the set of water table limits analysed.



Extent of waterlogging as a function of evaporation basin area

Similar to the water table analysis, functions were developed for the height of water in the basin and periods when the basin was completely full or dry. This allows for an assessment of the efficiency of the basin in evaporating maximum water with minimum area.

Table of Contents

List of Figures

List of Tables

Acknowledgments

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List of Variables

A_B	basin area (m^2)
A_F	farm area (m^2)
C_I	irrigation efficiency (-)
C_{PD}	maximum capacity of subsurface drainage system (mm/d)
d	equivalent ditch depth above impermeable layer (m)
D	recharge of water from unsaturated zone to water table (mm/d)
Di	depth of impermeable substratum below tile drains (m)
D_B	recharge of water in basin from unsaturated zone into water table (mm/d)
D_F	recharge from unsaturated zone to water table in farm (mm/d)
D_R	discharge from the soil below basin into basin storage (mm/d)
D_{RZ}	crop root zone thickness (m)
D_W	accumulated soil water deficit (mm)
D_{WC}	maximum allowable water deficit (mm)
E_B	evaporation from basin system (mm/d)
E_{BR}	open water evaporation from basin (mm/d)
E_{BS}	soil evaporation when basin is dry (mm/d)
E_{PS}	potential evaporation from basin assuming continuously ponded water at Δt (mm/d)
E_{SS}	potential evaporation from basin bottom when the soil is saturated (mm/d)
E_W	open water evaporation (mm/d)
ET_0	potential evapotranspiration (mm/d)
ET_C	crop evapotranspiration (mm/d)
F_B	Basin free board (m)
F_H	Net groundwater inflow into the model domain (m^3/d)
F_V	Net groundwater leakage from the model domain to the underlying strata (m^3/d)
h	water table head above pipe drains (m)
H_B	water table height in basin soil (m)
H_{BB}	height of basin bottom (m)
H_{BM}	temporary basin water table used for calculating interchange between farm and basin (m)
H_{DM}	total depth of study domain (m)
H_F	water table height in farm (m)

H_{FA}	management allowable water table height in farmland (m)
H_{FM}	temporary farm water table used for calculating interchange between farm and basin (m)
H_R	water level in basin (m)
H_{RA}	maximum managed water level in basin (m)
H_{RE}	maximum possible level in basin, i.e. totally full (m)
H_{RM}	variable describing whether basin is dry or ponded with water for a 1 day time step (mm)
H_{SM}	temporary water table variable used for calculating interchange between farm and basin (m)
H_{WL}	critical water table value at which the crop root zone is waterlogged (m)
I	irrigation (mm)
K_1	saturated hydraulic conductivity of soil above drains (m/d)
K_2	saturated hydraulic conductivity of soil below drains (m/d)
K_C	crop coefficient (-)
K_{SB}	saturated hydraulic conductivity of basin bottom (m/d)
K_{SF}	saturated hydraulic conductivity of soil in farm (m/d)
K_{ST}	saturated hydraulic conductivity of soil in Gardner equation (3-11) (m/d)
K_W	open water evaporation coefficient (-)
$K(\theta)$	hydraulic conductivity of soil (m/d)
L	interchange between basin and farmland (mm/d)
L_D	design drain spacing (m)
L_{PS}	leakage from basin when it is continuously ponded at Δt (mm/d)
L_R	leakage from basin into soil below (mm/d)
P	pumping from the drainage system (mm/d)
P_{max}	Maximum pumping rate from the drainage system (mm/d)
P_1	parameter in Van Genuchten equation (3-13) (v/v)
P_2	as above (cm)
P_3	as above (v/v)
P_4	as above, residual soil water content (v/v)
Q_L	total interchange L between farm and basin (m^3/d)
R	rainfall (mm/d)
R_B	average distance from the center of basin to farm (m)
R_{BF}	basin overflow (mm/d)
R_{FF}	farm runoff (mm/d)
R_θ	ratio of θ_{CR} to θ_{ST} (-)
S_{BD}	variable to record the boundary condition at basin bottom. S_{BD} = *'EVAPORATION'* or *'INFILTRATION'*

S_{FM}	variable to record soil status below basin. S_{FM} = *'SATURATED'* or *'UNSATURATED'*
T_G	depth of water table to soil surface (m)
u	wet entry perimeter of trench for drain (m)
U	upflow of water from water table into unsaturated soil zone (mm/d)
U_B	upflow from water table into unsaturated zone in basin (mm/d)
U_F	upflow from water table to unsaturated zone in farm (mm/d)
W	depth of pipe drains (m)
W_B	total water stored in basin soil (excluding water in basin) (mm)
W_B^*	water stored in whole basin soil profile at the end of Δt without considering overflow (m^3)
W_{BMX}	maximum water storage in basin soil profile (m^3)
W_{BS}	water stored in saturated zone of basin profile (mm/d)
W_{BS}^*	temporary variable to record water stored in basin saturated zone for the end of one time step without considering water table change (m^3)
W_{BSB}	water stored in the basin (m^3)
W_{BU}	water stored in unsaturated zone of basin profile (mm)
W_{BU}^*	temporary variable to record water stored in basin unsaturated zone for the end of one time step without considering water table change (m^3)
W_{BW}	water stored in whole basin system (mm)
W_F	total water stored in farm, both saturated and unsaturated zone (mm)
W_F^*	water stored in whole farm soil profile at the end of Δt without considering runoff (m^3)
W_{FMX}	maximum water storage in farm soil profile (m^3)
W_{FS}	water stored in saturated zone of farm (mm)
W_{FS}^*	temporary variable to record water stored in farm saturated zone for the end of one time step without considering water table change (m^3)
W_{FU}	water stored in unsaturated zone of farm (mm)
W_{FU}^*	temporary variable to record water stored in farm unsaturated zone for the end of one time step without considering water table change (m^3)
x	normalised soil water content (-)
z	vertical coordinate (m)
Z_R	distance between root zone reference and water table (m)
Z_{max}	threshold water table depth in equation (3-17) (m)
Z_{WF}	depth of the wetting front from the soil surface in Green-Ampt infiltration model (m)
α	exponential index in Gardner equation (3-11) (1/cm)
Δt	time step for numerical simulation (one day)
ψ	hydraulic head of soil water (excluding gravitational potential) (cm)
θ	volumetric water content of soil (v/v)

θ_B	average water content in the basin unsaturated zone (v/v)
θ_{BMN}	minimum value of basin soil water content above a water table (v/v)
θ_{CR}	maximum (critical) value of soil water content that the unsaturated zone can reach before saturation occurs (v/v)
θ_{DRY}	water content of basin soil when its evaporation becomes zero (v/v)
θ_{DUL}	drained upper limit, same as field capacity (v/v)
θ_F	average water content of soil in farm unsaturated zone (v/v)
θ_{FC}	field capacity (v/v)
θ_{FMN}	minimum value of farm soil water content above a water table (v/v)
θ_L	lower limit of plant available water (v/v)
θ_{RZ}	average soil water content within crop root zone (v/v)
θ_{ST}	saturated water content of soil (v/v)
θ_{TS}	variable used to examine the average water content of soil above water table (v/v)

1. Introduction

Evaporation basins are used around the world as a method of diverting saline drainage water from irrigation away from rivers, lakes, swamps and other natural water bodies. This is with the aim of protecting the interests of downstream water users and the natural ecosystems. In Australia there are many natural drainage areas that have existed as defacto evaporation basins and over time many large basins have been constructed, Evans (1989). These basins have usually taken the saline drainage water from large communities of irrigation farmers often with the purpose of preventing drainage to the river.

Smaller evaporation basins constructed on-farm to dispose of drainage from the surrounding farm are much less common than the bigger community basins. On-farm basins have been used in California to a small extent, in Australia on-farm evaporation basins are peculiar to the Murrumbidgee Irrigation Area (MIA) in southern NSW. This document reports on the development and testing of a water balance model used to investigate the hydrology of on-farm basins.

1.1 Background

On-farm evaporation basins have been used in the MIA since 1988. They were adopted as part of the MIA Land and Water Management Plan (L&WMP) in an effort to reduce the salt load leaving the area. The need to reduce salt loads leaving the MIA was brought about by pressure from downstream users of the drainage water. The salt balance for the MIA shows that about 40% of the salt load leaving the area is from the horticultural farms which have subsurface pipe drainage. These horticultural farms however only constitute about 15% of the area, van der Lely (1996). In addition to this the area of horticulture has steadily expanded since the late 1980’s to a peak of about 500 ha annually between 1995/97. In order that these new developments should not further increase the salinity of the MIA drainage by discharging their subsurface drainage water, a moratorium on off-farm discharge was introduced forcing growers to build on-farm evaporation basins.

Thus since 1989 about 15 on farm basins have been constructed with a total area of about 60 ha. These basins are used to store the drainage water from subsurface pipe (tile) drains installed about 2 m deep, spaced 20 to 40 m apart. The water from these drains has variable salinity from 3 to 20 dS/m. A summary of the basin conditions in the MIA in October 1997 is presented in Table 1-1.

Table 1-1. Summary data for on-farm evaporation basins in the MIA (October 1997)

	Average	Minimum	Maximum
Basin area (ha)	4.3	0.6	19.0
% of drained area	4.1	1.1	7.4
Drainage water EC (dS/m)	10	3	20
Basin water EC (dS/m)	20	8	45
Concentration factor Basin EC / Drainage EC	2.2	1.2	4.8

The design and management of these basins varies widely due to a lack of clear guidelines. Some basins are very small in comparison to the drained area and are thus nearly always full. However, at the time of the survey 50% of the basin area was dry. This is in part due to the drainage pumps being turned off (farmers deciding there is no need to drain) and in part due to relatively high basin leakage rates. The lack of salt concentration in the basin water is evidence of high leakage rates. Thus there already exists a significant number of on-farm basins which have highly variable physical attributes. Additionally, management of these basins and the associated subsurface drainage system varies from trying to keep the basins dry at one extreme to always keeping them full at the other.

Previous to this work there was little data gathered on these basins and the design guidelines were "best bet" with no follow up work to determine if the basins were functioning adequately. As part of a larger CSIRO project '*Managing disposal basins for salt storage in irrigation areas'*, monitoring of these on-farm basins was undertaken. This included intensive monitoring of a newly commissioned basin. Concurrent with this monitoring it was deemed that a theoretical framework was required that could be used to improve our understanding of the system. Thus a relatively simple water balance model was developed. The model was required to aid in understanding the interaction between the farm drainage system and the evaporation basin and thus the resultant farm water tables. This information could then be used to refine design and management guidelines.

1.2 Literature

Evaporation basins have been used around the world to store salt, Tanji et al (1993) and were considered by Evans (1989) as the most suitable salt disposal option for the Murray-Darling Basin.

The salinity working group of the Murray Darling Ministerial Council (1986) found that evaporation basins had a role to play as they could store salt if they were properly designed and maintained. There may even be some other advantages such as providing a wetland habitat for birds or even salt harvesting. However there were some concerns:

§ Lateral seepage may cause localised waterlogging and salinity around the basin;

§ The expected life of a basin was unknown, but may be short;

§ The costs of planning and constructing basins may be high;

§ There may be other negative environmental effects.

In regard to on-farm basins specifically, Tanji et al (1993) reported that there were 28 basins in the San Joaquin valley California, ranging in size from 2.5 to 730 ha. New basins were no longer constructed and some had actually been closed down due to accumulation of Selenium in the waters which was having adverse effect on bird life. In Australia a number of studies of on-farm basins have been conducted. Girdwood (1978) conducted water balance studies on a 3 ha basin, receiving water from a shallow tube well. Seepage was estimated at various intervals over a 4 year period and some soil samples were taken from the farm at the beginning and end of the study. However the farm water balance was not monitored, nor the effect of pumping, or the basin, on farm water tables. Other studies of evaporation basins have also focussed on the seepage rates, Grismer et al (1993), McCullogh-Sanden and Grismer (1988), Otto (1994). McConachy (1991) describe in detail the design process for a tile drainage and evaporation basin demonstration site. The depth of water in the basin is modelled as is the basin water salinity and leakage rates, however the effect on farm water tables is given little consideration.

All authors recognise the difficulty of estimating the required evaporation basin area, Tanji et al (1985) suggested that the required basin area in the San Joaquin valley could be as little as 3 % or as much as 33 % of the drained area. Table 1-2 shows various estimates of basin areas required, however these figures are derived from gross annual water balances. This does not take into consideration temporal variations in climate, crop growth stage or management.

Table 1-2. Percentage of drained area required for evaporation basin

Location	Typical	High	Reference
California	15	25	Hanson 1984
California	10 - 15	50	Grismer et al 1993
California	3 -15	33	Tanji et al 1985
Pyramid Hill, Victoria	19		Mann (pers comm)
Wakool, NSW	4		Creagh 1991
Girgarre, Victoria	3	10	RWC 1992
MIA, NSW	1 - 7	10 *	* recommended by DLWC Griffith

Muirhead et al (1997) recognised that irrigation and drainage management will have a large impact on the required basin area. Table 1-3 shows their estimate of the effect of different irrigation efficiencies on the area required.

Table 1-3. Effect of irrigation efficiency on the drainage rate and basin ratio (Muirhead et al 1997)

Irrigation Efficiency*	Drainage Rate (Ml / ha / yr)	Basin Ratio (%)	
		No Seepage	Seepage (2 mm/day)
Low	3.0 - 4.0	30 - 40	18 - 24
Medium	2.0 - 3.0	20 - 30	12 - 18
High	1.0 - 2.0	10 - 20	6 - 12

* Low - Flood irrigation, grades < 1:700, water tables < 1.2m

Med - flood irrigation, grades >1:700, water tables >1.5m

High - micro-irrigation, water tables >1.5m

Again the above results were derived from gross water balances assuming steady state inputs to the basin. All the work regarding evaporation basins has focussed mainly on the basin itself especially seepage rates, basin water height and salinity of the water. A dynamic linkage between the drainage system on the farm and the basin has not been attempted, inputs to drainage basins have been modelled as steady state daily or monthly quantities. There has been no attempt to assess the effect of an evaporation basin on the operation of the drainage system. For instance if the basin is full further pumping of the drainage system is prevented. This will have an adverse effect on the water table status in the farm area. Other management factors such as irrigation amount/timing and the management of the drainage system have had little consideration.

Muirhead et al (1997) state that further research needs for on-farm evaporation basins include:

§ Effects of leakage rates (lateral and deep) and the effect of depth of clay layer, compaction during basin construction, microbial activity, salinity of ponded water and hydraulic head. Also the effect of plastic membrane on preventing seepage;

§ Effect of irrigation method, layout and depth to the water table on the discharge from subsurface drains;

§ Water and salt balance of existing basins, and the rate of movement of salt in deep seepage;

§ Effect of management of tile drain installation on seasonal discharge and on waterlogging and salt protection to the crop.

Apart from the above considerations there has also been little attempt to include the effect of climate variability on the operation of the basin, hence the effectiveness of the drainage system and critically the effect on the farm water tables. A lack of quantitative analysis of the performance of on-farm evaporation basins in controlling water tables and salinity in the root zone have resulted in a wide range of recommendations with no indication of the possible impacts of varying the size of the basin. There has also been little work on optimising basin area against adequate water table control and area of lost production to the basin.

2. Basic Framework

2.1 Initial Assessment

A farm that has an on-farm evaporation basin is a complicated agricultural ecosystem. In this system, there are two discrete units. One is the farmland, the other is the evaporation basin, Figure 2-1. These two subsystems behave differently in many respects.

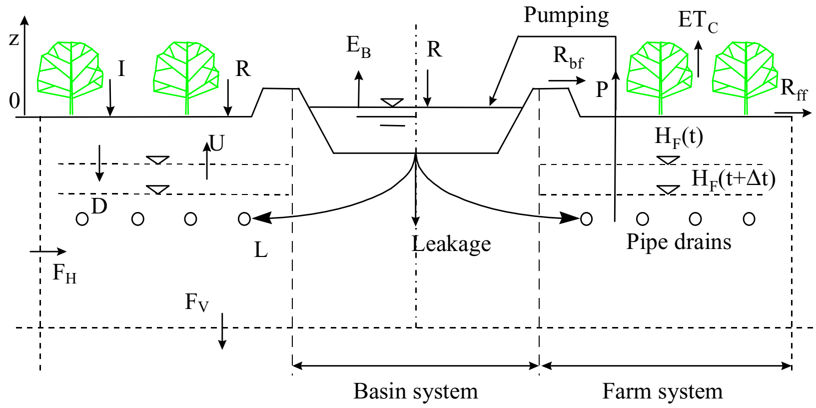

Figure 2-1. Conceptual diagram of on-farm evaporation basin system

In the farm system, there is normally an unsaturated zone and saturated zone. There is recharge or discharge between these two zones. To meet crop water requirements, irrigation is required, thus irrigation management needs to be considered. In order to prevent waterlogging and salinisation in the crop root zone, drainage is needed, especially in areas of high water tables and poor irrigation practice. Thus drainage design and management needs to be considered. Evapotranspiration is the main water use. It plays a crucial role in determining the irrigation requirements and the water distribution between the farmland and evaporation basin.

The evaporation basin services the farm by storing and evaporating drainage water. The water in the basin is different from soil water as it evaporates at an open water rate. Unless the basin is artificially sealed, there is leakage into the soil below the basin. This leakage can result in water exchange between the basin and farm, which redistributes water and hence salt back to the farmland. Under certain circumstances, the basin can also dry out and the basin soil becomes unsaturated.

The dynamics of the total system are highly dependent upon the irrigation and drainage management, which result in inputs to the basin. The ability of the basin to manage the drainage water will be dependent upon its evaporative potential. Thus the required basin area will be a result of both physical and management variables. These complex relationships are most usefully explored by developing a model.

2.2 Scope of the Model

If the system is to be modelled, then the scope and complexity of the model needs to be considered.

The background and literature survey indicate that on-farm evaporation basins exist in many forms and scales. From small below ground basins to large above ground basins, which can be ponded or dry. There is also a variety of cropping and irrigation systems. These variations obviously reflect the biophysical factors, but perhaps to a greater extent the design and management factors. This diversity could lead to the development of a highly complex model requiring a large investment or alternatively a simple but generic model.

This study investigates the hydraulic relationships between farm and evaporation basins to enable a long term assessments of such a system and allow for optimisation in design and management. This requires quantitative analysis of the system but with an emphasis on capturing the relationships for assessment over long periods rather than a detailed predictive capacity. Thus cumulative or general effects are more important than the exact conditions on any particular day. Understanding the ranges of values and their sensitivity to various components is also more valuable than trying to predict the exact conditions at a particular time. The diversity in design and management practices also requires a generic model with a high degree of flexibility that can encompass as much of this diversity as possible. It is important that all the hydraulic relationships between the farm and evaporation basin and their dynamic variation are modelled. This should be done with equal emphasis on the farm system and basin system. These aims would most easily be achieved using a simple water balance model. In this context detailed modelling of the farm and basin shape and the basin position within the farm is not required. Thus in the model, the basin can be assumed to be located at the center of the farm and that the farm has an arbitrary shape. A one day time step can be used because the available meteorological data is in a daily format, which is adequate for long term modelling.

Since at this time there has been little previous work on the farm with basin system a simpler generic model is justified. If subsequently there is need for a greater understanding of the physical processes then detailed numerical modelling can be undertaken.

2.3 Objectives and Constraints

The objectives of this modelling work are as follows:

- Better understand the hydraulic relationships between farmland and basin system;
- To provide a tool to aid in the design of on-farm basins to minimise basin area whilst controlling waterlogging;

In order to meet these objectives within time and data constraints, a simple water balance model called 'BASINMAN' was developed within the following constraints:

- The model would represent a single farm with on-farm evaporation basin system;
- Water movement would be modelled but not solute transport;
- The model would be designed for horizontal pipe drainage (tile drains) only;
- The model area is assumed flat;
- The basin is assumed circular in the centre of the farm area;
- Net inflow to, and leakage from, the model domain is set to a static value for each simulation;
- The model should represent the system with easily available data;
- The outputs from the model should clearly and easily show the main physical processes and key limiting factors.

How each physical process in the 'BASINMAN' model has been described is outlined in the following sections.

3. Farm Processes

3.1 Evapotranspiration

Crop actual evapotranspiration ET_C (mm/d) is represented as a function of crop coefficients and potential evaporation. In this model ET_C is calculated using

$$ET_C = K_C \times ET_0 \tag{3-1}$$

Where

K_C : crop coefficient

ET_0 : Potential evapotranspiration (mm/d)

Simulations for the MIA were conducted using ET_O data supplied by CSIRO Land and Water Griffith. The Crop coefficient values used for the MIA have also been developed by CSIRO Land and Water, Griffith Table 3-1.

Table 3-1. Crop coefficients for the MIA, after Meyer W. (1996), pers. comm.

CROP	Sow date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice	15-Oct	1.1	1.1	1	0.4	0.2	0.2	0.2	0.3	0.4	1	1.1	1.1
Wheat	15-May	0.2	0.2	0.2	0.3	0.4	0.6	0.9	1.05	1.05	0.8	0.5	0.2
Oats	20-Apr	0.2	0.2	0.2	0.3	0.5	0.8	1	1.05	1.05	0.7	0.3	0.2
Barley	31-May	0.2	0.2	0.2	0.3	0.35	0.5	0.8	1	1	0.9	0.5	0.2
Maize	1-Nov	0.85	0.85	0.6	0.3	0.3	0.4	0.4	0.4	0.3	0.35	0.5	0.7
Canola	30-Apr	0.2	0.2	0.2	0.3	0.4	0.6	0.7	0.75	0.75	0.7	0.4	0.2
Soybean	30-Nov	0.75	1.05	1	0.5	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.45
Summer pasture	1-Sep	0.85	0.85	0.85	0.85	0.8	0.8	0.8	0.8	0.8	0.85	0.85	0.85
Winter pasture	25-Mar	0.2	0.2	0.2	0.4	0.6	0.7	0.8	0.8	0.8	0.6	0.4	0.2
Lucerne	1-Oct	1.3	1.3	1.2	1.2	1	0.65	0.65	0.65	0.9	1.2	1.3	1.3
Vines	1-Sep	0.6	0.5	0.5	0.4	0.3	0.3	0.4	0.4	0.45	0.5	0.5	0.5
Citrus	1-Jul	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
Stone fruit	1-Sep	0.8	0.8	0.8	0.8	0.7	0.4	0.4	0.4	0.5	0.65	0.75	0.8
Winter Veg.	1-Apr	0.2	0.2	0.2	0.4	0.5	0.55	0.55	0.5	0.5	0.3	0.3	0.2
Summer Veg.	30-Aug	0.65	0.6	0.4	0.3	0.3	0.4	0.4	0.4	0.5	0.6	0.65	0.65
Fallow		0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.2
Notes: Most values from lysimeter/field measurements, values for canola/vegetables educated guesses.													
For pastures/lucerne, values assume cover is not grazed or mown. Mown lucerne/pasture use a K_c of about 0.4.													
Interpolation between the points is recommended rather than using values as step wise histograms.													

3.2 Irrigation

Irrigation requirements can be determined either very simply or using quite sophisticated methods. For the former case, irrigation is carried out based on farmers' experience and common farming practices. For the latter case, irrigation can be determined by measuring soil water content. Control of the irrigation amount can also vary in its accuracy. With flood and furrow irrigation the amount applied is imprecise, with sprinkler and drip irrigation the amount can be precisely controlled.

Within the model irrigation can be taken as either a known or unknown quantity according to the aim of the simulation. As a known item, it is based on existing records and can be used directly as input data. For the purpose of long term design and management of an on-farm basin irrigation is treated as an unknown quantity and is simulated.

The first attempts to simulate irrigation were by using the average soil water content in the crop root zone, controlled with an irrigation set point. Irrigation is thus required when:

$$\text{Average soil water content within crop root zone } (\theta_{RZ}) = C \times \text{field capacity } (\theta_{FC}) \quad (3\text{-}2)$$

Where $0 < C < 1$. The C value is set with regard to the crop type and irrigation method. For example the ratio of wetted area by sprinkler or flood irrigation to the whole area is large; whereas for drip irrigation this ratio can be quite small therefore a much lower value of C would be used to simulate drip irrigation.

With this method a separate soil layer for the crop root zone is required. However the model consists of only two soil layers: unsaturated and saturated. In order to use the average soil water content, the water content in the crop root zone had to be transformed from that of a general soil layer above the water table. This was a major limitation of this method.

Running simulations using this method gave unsatisfactory results in that irrigation tended to fluctuate excessively. This was found to be due to the fluctuating depth to the water table. With deep water tables, there were large amounts of soil water available resulting in large irrigation intervals. However when the water tables became shallow, frequent irrigation occurred as the available soil water was restricted, this in turn maintained the shallow water table.

To overcome the above problems with irrigation, an alternative method was developed using crop evapotranspiration. For a long-term crop water balance, it can be assumed that:

$$\text{Evapotranspiration } (ET_C) \approx \text{Irrigation } (I) + \text{rainfall } (R) \quad (3\text{-}3)$$

The soil water deficit (D_W) can be represented as $ET - R$, and irrigation I is the water needed to replace the soil water deficit. Based on these principles, irrigation can be simulated by considering:

§ Accumulated soil water deficit;

§ Maximum allowable water deficit (D_{WC});

§ Rainfall events.

Different crops and irrigation methods will allow different D_{WC} . If rainfall occurs, this offsets some ET_C and defers irrigation. In reality, irrigation practice is not 100% efficient, generally more water is applied than is actually required. The level of irrigation efficiency (C_I) needs to be introduced. The input irrigation efficiency C_I is the ratio of water applied I to water deficit D_{WC}.

Table 3-1. Typical C_I *values for horticulture, after Cock et al. (1991), Christen pers. com.*

Flood	1.5 - 2.0
Furrow	1.3 - 1.8
Sprinkler	1.1 - 1.5
Drip	1.1 - 1.3

Simulation of the irrigation processes is described by the following equations.

$$D_W(t-1) = \sum_{t_s}^{t-1} ET_C - \sum_{t_s}^{t-1} R \quad (3\text{-}4)$$

Where t_S is the time at which the last irrigation occurred.

§ If $D_W(t-1) >= D_{WC}$ and $R(t)=0$, then

$$I(t)=C_I \times D_W(t-1) \quad (3\text{-}5)$$

§ Else

$$I(t)=0 \quad (3\text{-}6)$$

This method of irrigation simulation is simple to implement. The limitation is that it doesn't consider actual soil water conditions, however that is close to the reality in much irrigation practice, leading in most instances to a tendency to over irrigate. Also, the delaying of irrigation due to rain, even if only a small amount, is common farming practice. Preliminary results show that the irrigation regime simulated by this method is close to practice seen in the field.

3.3 Recharge

Recharge is the process of water reaching the water table from the unsaturated zone. This model estimates recharge by using a modified tipping bucket mechanism which takes account of the soil hydraulic properties. That is recharge (*D*) is limited to:

§ Hydraulic conductivity of soil $K(\theta)$;

§ Water storage in the "bucket".

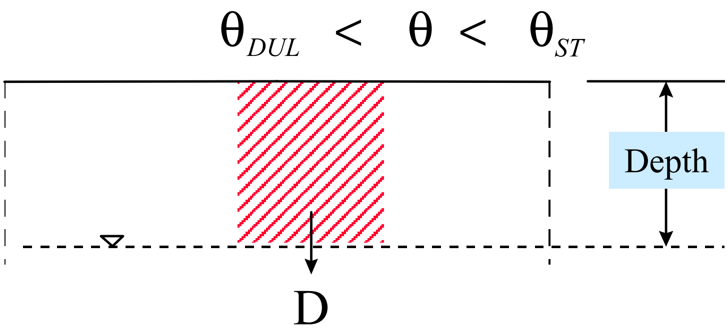

Figure 3-1. Conceptual diagram for estimating recharge to groundwater

Figure 3-1 is an illustration of this tipping bucket. Where,

θ_{DUL} : drained upper limit

θ : volumetric water content of soil

θ_{ST} : saturated water content of soil

D (mm/d) is represented by:

1. If $\theta < \theta_{DUL}$, then

$$D=0 \qquad (3\text{-}7)$$

2. Else if $\theta > \theta_{DUL}$, then

$$D = K(\theta) \qquad (3\text{-}8)$$

§ If $K(\theta) < (\theta - \theta_{DUL}) \times \text{Depth}/1 \text{ day}$, then

$$D = (\theta - \theta_{DUL}) \times Depth/1\ day \tag{3-9}$$

§ Else

$$K(\psi) = K_{ST} \quad ; \quad \psi \geq 0 \tag{3-10}$$

$$K(\psi) = K_{ST}\exp(\alpha\psi) \quad ; \quad \psi < 0 \tag{3-11}$$

In order to get the recharge rate, the hydraulic conductivity of the soil $K(\theta)$ is required. In this model, this is simply done using the Gardner equation (Gardner, 1958):

Where K_{ST}: saturated hydraulic conductivity of soil (m/d)

α: empirical index (1/cm)

ψ: hydraulic head of soil water (excluding gravitational potential) (cm)

ψ is composed of two parts: soil matric potential (ψ_S) and pressure of free water (ψ_W). When $\psi \geq 0$, the soil is saturated and ψ_S is zero. When $\psi < 0$, the soil is unsaturated and ψ_W is zero. Normally the soil water content rather than soil matric potential is used. ψ can be obtained from θ from a water retention curve of the soil $\theta(\psi)$. This model uses the Van Genuchten equation (Van Genuchten, 1980) to develop the soil water retention curve.

$$\theta = \theta_{ST} \quad ; \quad \psi \geq 0 \tag{3-12}$$

$$\theta = \frac{P_1 P_2}{P_2 + |\psi|^{P_3}} + P_4 \quad ; \quad \psi < 0 \tag{3-13}$$

Where P_1, P_2 (cm), P_3, P_4 are regression parameters. P_4 is the residual soil water content. P_1, P_4 meets the relation:

$$P_1 + P_4 = \theta_{ST} \tag{3-14}$$

From above (3-12), (3-13) $\theta(\psi)$ equation, ψ can be written as:

$$\psi \geq 0 \quad ; \quad \theta = \theta_{ST} \tag{3-15}$$

$$\psi = -10^{\left(\frac{1}{P_3}\lg\left(\frac{P_2(P_1+P_4-\theta)}{\theta - P_4}\right)\right)} \quad ; \quad \theta < \theta_{ST} \qquad (3\text{-}16)$$

To obtain $K(\psi)$ and $\theta(\psi)$ for a particular site is difficult. To overcome this difficulty, a set of generalised hydraulic parameters for common soils has been provided in Table 3-2.

Table 3-2. Generalised hydraulic parameters for common soils (after Wu 1996)

Soil type	P_1	P_2	P_3	P_4	K_{ST}	α
		(cm)			(cm/min)	(1/cm)
Heavy clay	0.28	70.030	0.66	0.27	6×10^{-6}	0.002
Light clay	0.28	50.159	0.63	0.16	6×10^{-5}	0.005
Silt Clay	0.31	175.995	0.80	0.11	6×10^{-4}	0.01
Loam	0.32	186.441	0.86	0.09	0.006	0.02
Light sand loam	0.28	247.682	0.92	0.09	0.06	0.03
Loamy sand	0.32	377.408	1.21	0.09	0.2	0.04
Sand	0.35	1617.929	1.68	0.04	0.6	0.05

3.4 Upflow

Upflow (U) occurs due to the potential difference between the saturated lower soil layers (water table) and drier upper layers. This potential difference occurs both from direct evaporation at the soil surface and transpiration via roots. Under field conditions, a shallow water table can contribute considerably to plant water use and therefore reduce irrigation requirements. There are many factors affecting upflow, thus it is difficult to describe analytically. This model adopts a mechanism for upflow from the water table using an empirical relationship developed by Meyer (pers.comm.). This mechanism relates upflow with the depth to water table, soil type, root zone and soil water content above the water table.

$$\frac{U}{ET} = \frac{a}{e^{b\left(\frac{z_R}{z_{max}}\right)}\left(1+e^{\frac{c}{x+0.01}}\right)} \qquad (3\text{-}17)$$

Where a , b , c are regression coefficients. a = 3.9, b = 3.8, c = 0.5, derived using data in Talsma (1963). Z_R is the distance from the top third of the root zone to the water table surface, As illustrated in Figure 3-2.

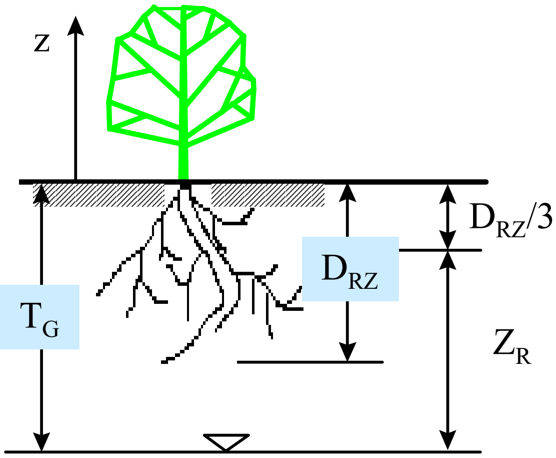

Figure 3-2. Illustration of the distance of crop root zone above water table surface

If the depth of root zone is written as D_{RZ} and the water table depth as T_G , then Z_R can be obtained from the following equations:

§ If $|T_G| \geq D_{RZ}/3$, then

$$Z_R = |T_G| - D_{RZ}/3 \qquad (3\text{-}18)$$

§ Else

$$Z_R = 0 \qquad (3\text{-}19)$$

In equation (3-17), Z_{max} is a threshold water table depth below which upflow would be less than 1mm/d which is defined by Talsma (1963). Values of Z_{max} related to soil texture have been derived by Meyer (pers. comm.).

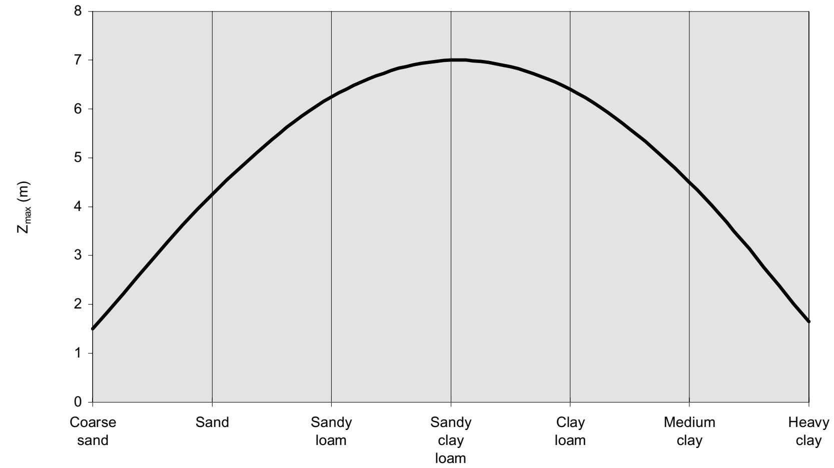

Figure 3-3. Z_{max} Varying with soil texture

the normalised soil water content x in equation (3-17), is described by the expression:

$$x = \frac{\theta_{ST} - \overline{\theta}}{\theta_{ST} - \theta_L} \qquad (3\text{-}20)$$

Where $\overline{\theta}$: average water content of unsaturated soil layer

θ_L : lower limit of plant available water

Figure 3-4 is a graph showing the relationship between upflow, water table depth and soil water content.

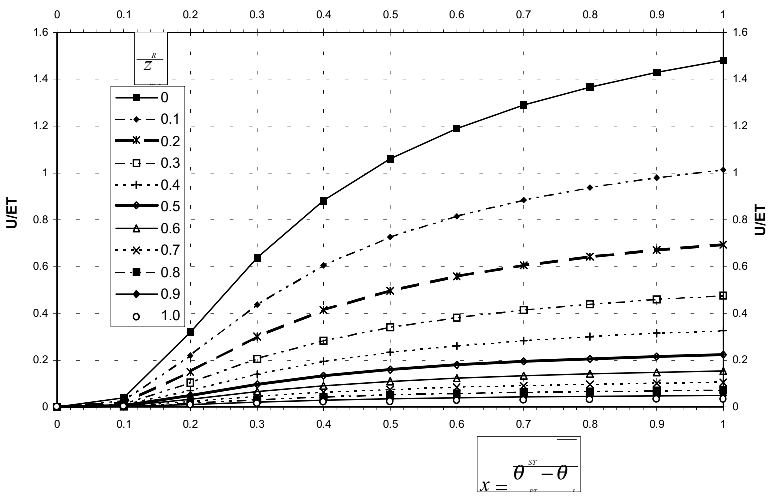

Figure 3-4. Upflow as a function of water table and soil water content

In Figure 3-4, it can be seen that there are situations when calculated *U/ET* is greater than 1, this is impossible. In the model, *U/ET* is confined to an upper limit of 1.

The estimation of upflow from the water table when there is a bare soil is slightly different, as described in section 4.4, page 29.

3.5 Subsurface Drainage

This model simulates a subsurface drainage system with horizontal pipe drains. The capacity of the system is designed according to the drainage requirement.

The operation of the system is related to the status of the basin water storage. If the water volume in the basin exceeds an allowable limit, then pumping is stopped to prevent overflow. This limit corresponds to an allowable water level in the basin (H_{RA}). This is the normal water storage level. In this model, a 0.1m height in the basin is given to accommodate storms, this is the basin freeboard. Also for management of the drainage system, the free board should have the capacity to hold the maximum rate of the drainage system (C_{PD} , mm/d) for one day. Thus the height of free board (F_B , m) required in the basin is set by:

$$F_B = 0.001 \times C_{PD} \times 1.0 \times A_F / A_B + 0.1 \qquad (3\text{-}21)$$

Where A_F : drained area (hectare)

A_B : basin area (hectare)

In the MIA, C_{PD} is normally 5 mm/d for light soils and 2.5 mm/d for heavy soils.

The pumping $P(t)$ (mm/d) of the drainage system is controlled by:

§ Water table height in the farmland (H_F);

§ System capacity, (P_{max});

§ Water level in basin (H_R) in relation to the maximum allowable basin level H_{RA} .

The allowable water table limit in the farm is denoted by H_{FA} . It is input as a single value or can be varied temporally. Drainage volumes are determined using the Hooghoudt drainage principle. In a horizontal drainage system, water a large distance away from a drain will tend to flow horizontally towards the drain. As the flow approaches the drain the flow will become radial to the drain. In Figure Figure 3-5 the 'real case' depicts a simplified schematic of this flow process. In the Hooghoudt drainage principal this flow pattern is transformed into an 'equivalent case', Figure 3-5. Drainage rates are then calculated for the simpler 'equivalent case, where only horizontal flow is considered. This is done by applying a transformation formula to the height of the drains above the impermeable base *(Di)*, in order to determine the equivalent depth *(d)* used in the drainage formula.

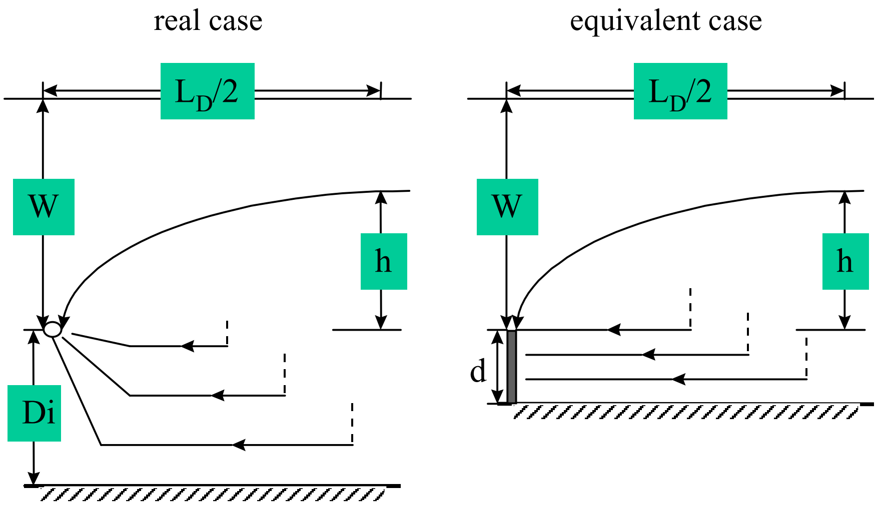

Figure 3-5. Transformation underlying the Hooghoudt drainage principle (after Smedema and Rycroft, 1983)

P(t) is calculated using the following:

§ If $H_F(t)<H_{FA}$, then

$$P(t)=0 \quad (3\text{-}22)$$

If $H_F(t)>H_{FA}$, but $H_R(t)>H_{RA}$, then

$$P(t)=0 \text{ (If basin is full then no drainage)} \quad (3\text{-}23)$$

If $H_F(t)>H_{FA}$, and $H_R(t)<H_{RA}$, then

$$P(t)=\frac{8K_2dh}{L_D^2}+\frac{4K_1h^2}{L_D^2} \text{ (Hooghoudt spacing formula)} \quad (3\text{-}24)$$

§ If $P(t)> P_{max}$ then $P(t)= P_{max}$

In equation (3-24) above:

$P(t)$: drainage rate (mm/d) (to be determined)

P_{max}: maximum allowable drainage rate (mm/d) (model input)

L_D : drain spacing (m) (model input)

K_1 : saturated hydraulic conductivity of soil above drains (m/d) (model input)

K_2 : saturated hydraulic conductivity of soil below drains (m/d) (model input)

d : equivalent depth above the impermeable base (m) (calculated using formulas below)

h : head above drains (m), derived from farm water table (H_F) using:

$$h = H_F - W \tag{3-25}$$

Where W is field drainage base (m). That is the depth at which the pipe drains are laid.

The depth between the drains and the impermeable substratum is written as Di (m). The equivalent depth d is calculated using the following expressions after Smedema and Rycroft (1983):

$$d = \frac{Di}{\frac{8Di}{\pi L_D} \ln \frac{Di}{u} + 1} \qquad \text{(for } Di < 0.25L_D\text{)} \tag{3-26}$$

$$d = \frac{\pi L_D}{8 \ln \frac{L_D}{u}} \qquad \text{(for } Di > 0.25\, L_D\text{)} \tag{3-27}$$

Where, u is wet entry perimeter of the trench for the drain (m) (model input). For trenches of 20-25cm width, typically u = 0.3-0.4m. In the MIA, u is about 0.3m.

4. Basin Processes

4.1 Possible Hydraulic Conditions

To describe the basin system, it is divided into two main parts: the basin and the soil below the basin. The Basin is formed by the surrounding banks and bottom. If there is water in the basin, then the water level is greater than zero; if the basin is dry, then the water level is equal to zero. The soil below the basin can be saturated or unsaturated. If the soil is saturated, then the water content is equal to the saturated soil water content (θ_{ST}) and the water table is the water level in basin. If the soil below the basin is unsaturated, then there is an unsaturated soil water content and a water table. The basin system has three working conditions:

- Condition 1: Basin ponded, basin soil saturated
- Condition 2: Basin dry, basin soil unsaturated
- Condition 3: Basin ponded, basin soil unsaturated

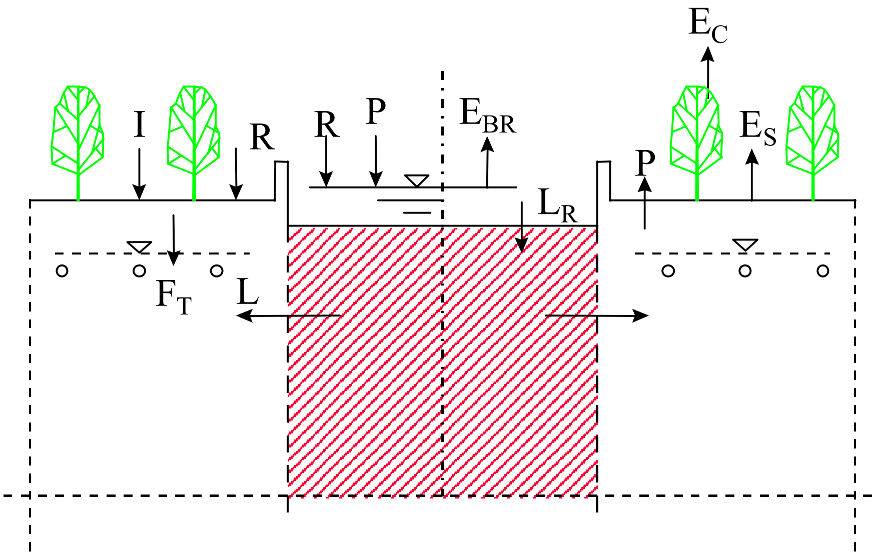

Figure 4-1. Basin ponded, basin soil saturated

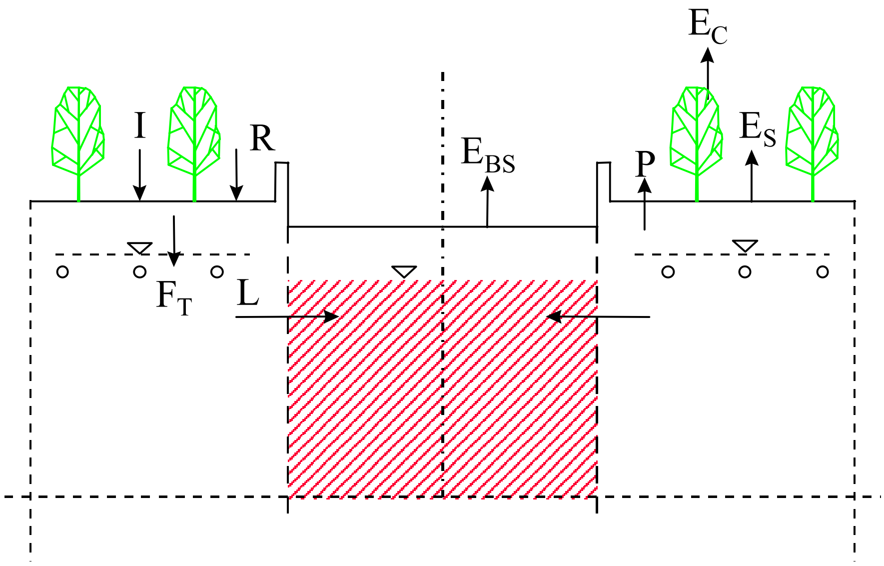

Figure 4-2. Basin dry, basin soil unsaturated

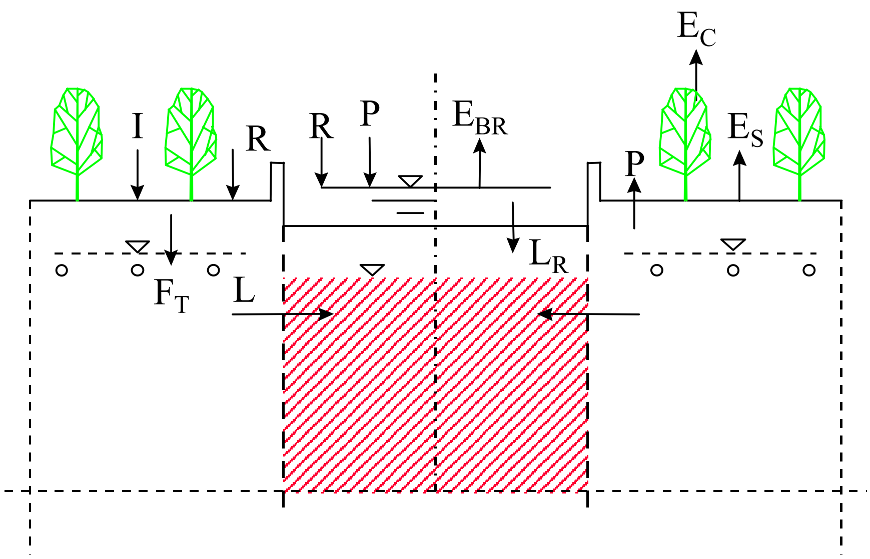

Figure 4-3. Basin ponded, basin soil unsaturated

4. Basin Evaporation

When the basin has water, evaporation is at an open water rate. When the basin is dry, evaporation is that from bare soil. This model estimates the open water evaporation rate (E_W , mm/d) from a potential evaporation rate (ET_0):

$$E_W=K_W \times ET_0 \qquad (4\text{-}1)$$

Where K_W is an open water evaporation coefficient.

When the basin is dry, the evaporative surface is the soil at the basin bottom. A simple approximation is used for the evaporation from the basin soil. When the soil below the basin is saturated, evaporation from the soil surface is at the rate of open water. Under unsaturated conditions, if the soil is very dry and its water content reaches a low critical value (θ_{DRY}), its evaporation becomes zero. As the soil water content reduces from θ_{ST} to θ_{DRY} , evaporation is reduced linearly. Thus the basin soil evaporation (E_{BS}) is expressed as:

§ If $\theta = \theta_{ST}$, then

$$E_{BS} = E_W \tag{4-2}$$

§ If $\theta_{DRY} < \theta < \theta_{ST}$, then

$$E_{BS} = \frac{\theta - \theta_{DRY}}{\theta_{ST} - \theta_{DRY}} E_W \tag{4-3}$$

§ If $\theta < \theta_{DRY}$, then

$$E_{BS} = 0 \tag{4-4}$$

In this model, the unsaturated soil zone is one layer. So, when using the above equations, θ represents the average soil water content in the unsaturated zone and θ_{DRY} corresponds to a lower limit of θ when $E_{BS} = 0$.

4.3 Basin Leakage and Discharge

Basin leakage (L_R , mm/d) in this model specifically refers to the quantity of water infiltrating from the basin into the soil directly below the basin. Thus leakage only occurs when basin has water. Basin discharge (D_R , mm/d) is the quantity of water moving from the soil below basin into basin storage. This occurs when the water table in the farm is higher than the water level in the basin and the basin soil is saturated.

4.3.1
Basin Operation with Saturated Conditions

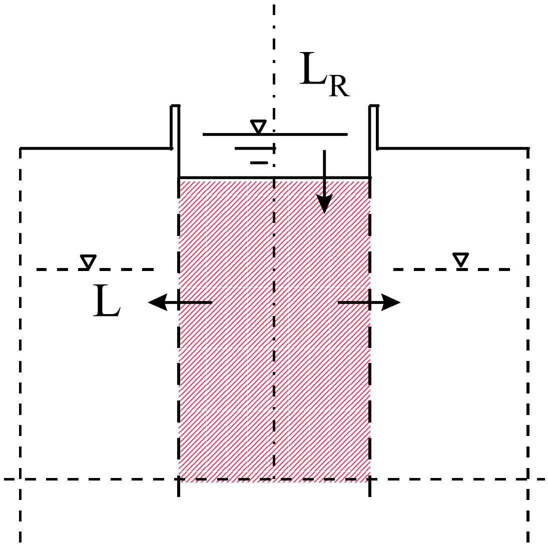

Figure 4-4. Leakage from basin into soil

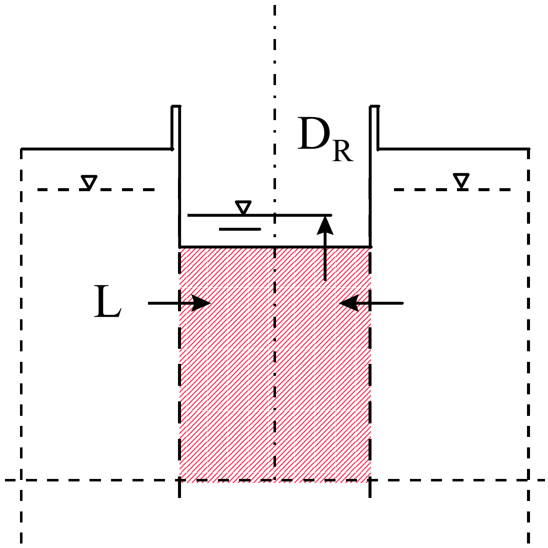

Figure 4-5. Discharge from farm into basin

In the above case, L_R is controlled not only by the hydraulic conductivity of the soil at the basin bottom, but also by the hydraulic relationship between the basin and farm. Figure 4-4 shows the situation when there is leakage. Figure 4-5 shows the discharge situation. In both figures, L is the interchange between basin and farm. When there is water flow from the basin into farm, L is positive, and when the reverse occurs L is negative. The determination of L is by Darcys' Law using the head difference between the basin and farm, this is fully explained in section 0, page 31.

In this system, the saturated hydraulic conductivity of the soil at the basin bottom (K_{SB} , m/d) will determine the maximum leakage rate from the basin. Assuming basin leakage is at the rate of K_{SB} :

$$\text{Assuming basin leakage } L_R^* = 1000 \times K_{SB} \quad (4\text{-}5)$$

Then the following conditions apply:

§ If $L > 0$ and $L_R^* > L$, then leakage is controlled by the basin to farm flux:

$$L_R = L \quad (4\text{-}6)$$

$$D_R = 0 \quad (4\text{-}7)$$

§ Else if $L > 0$ and $L_R^* < L$, then leakage is controlled by the basin bottom layer:

$$L_R = L_R^* \tag{4-8}$$

$$D_R = 0 \tag{4-9}$$

§ Else if $L < 0$, then

$$L_R = 0 \tag{4-10}$$

$$D_R = |L| \tag{4-11}$$

4.3.2 Basin Operation with Unsaturated Conditions

In this case, the determination of basin leakage is more difficult best solved numerically. However, to avoid complexity, the basin leakage is approximated analytically.

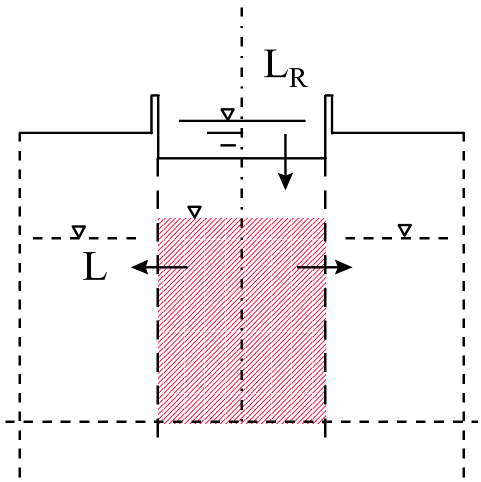

Figure 4-6. Leakage when L > 0

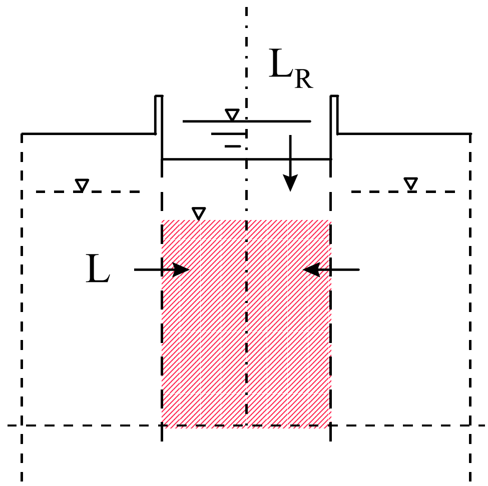

Figure 4-7. Leakage when L < 0

The two figures above are the situations when leakage occurs from ponded water in the basin into unsaturated soil. To simulate this simply, leakage is set at the rate of saturated hydraulic conductivity. That is:

$$L_R = 1000 \times K_{SB} \tag{4-12}$$

This model also has the option to use the Green-Ampt infiltration model. In this model, water is assumed to enter the soil as a slug resulting in a sharply defined wetting front. Above this front, the soil has been wetted to saturation; below this front, the soil remains at the initial moisture content of the soil profile.

When using the Green-Ampt model to calculate infiltration quantity and rate, the depth of wetting front needs to be calculated. The wetting front equation relates the development of the wetting front with time, ponded water depth at soil surface, saturated hydraulic conductivity of soil and soil suction at the wetting front. This equation is an implicit one of the depth of wetting front. By numerically solving this equation for roots using the binary splitting method, we can get the depth of wetting front, and thus the leakage rate from the basin into unsaturated soil.

The infiltration process in evaporation basins is quite complicated and related to many factors, both physical and microbiological. The BASINMAN model provides the above two methods as user options. Estimating leakage by hydraulic conductivity is easier to model and requires minimal soils data, thus it is the recommended method for most circumstances.

Analysing Figure 4-6 and Figure 4-7, it can be seen that leakage L_R is also controlled by the soil storage below the basin. For simplicity, this model neglects this factor. However, if L_R is overestimated causing the water volume in the specified soil zone below the basin to exceed the maximum storage of the zone, then this is managed by some discharge D_R into the basin storage. This mechanism will be presented in detail in section 7.2 and 0.

In reality, this compensatory discharge D_R can not occur in Figure 4-6 where $L > 0$, and in Figure 4-7 where although $L < 0$, the water table in the farm is lower than the basin bottom. If this occurs during modelling, it is due to the limitation of numerical simulations using fixed flux rates during a time step or due to the simplifications of the calculations outlined above.

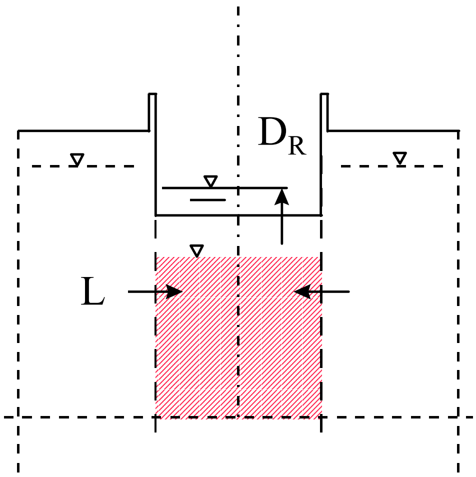

Figure 4-8. Discharge when basin has water

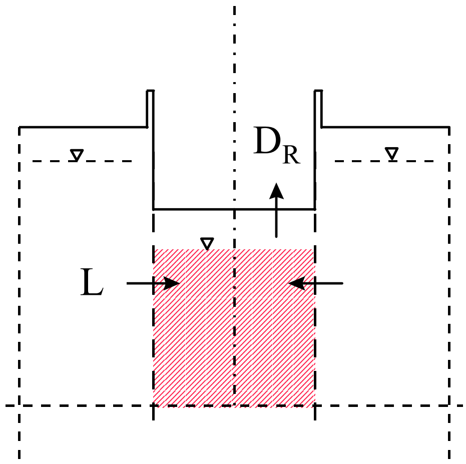

Figure 4-9. Discharge when basin is dry

In Figure 4-8 and Figure 4-9, water tables in the farm are above the water level in the basin or above the basin bottom. In these situations, discharge D_R may occur during the period of one time step. The model manages these cases in the same manner as previously for the situations in Figure 4-6 and Figure 4-7. That is both the occurrence and magnitude of D_R are determined by comparing the water volume below the basin at the end of Δt with the maximum storage of the zone.

4.4 Basin Recharge and Upflow

When the soil below the basin is unsaturated, there exists a water table and above this an unsaturated zone. Below this level is a saturated zone. Under this condition, there occurs water exchange between these two zones. In this model, basin recharge (D_B , mm/d) refers to the process of water moving from the unsaturated zone into the water table. Basin upflow (U_B , mm/d) refers to the process of water moving from the water table into the unsaturated zone. U_B is driven by soil evaporation at the basin bottom. Thus it only occurs when the basin is dry. Figure 4-10 is a case when recharge occurs. Figure 4-11 is a case when both recharge and upflow occur.

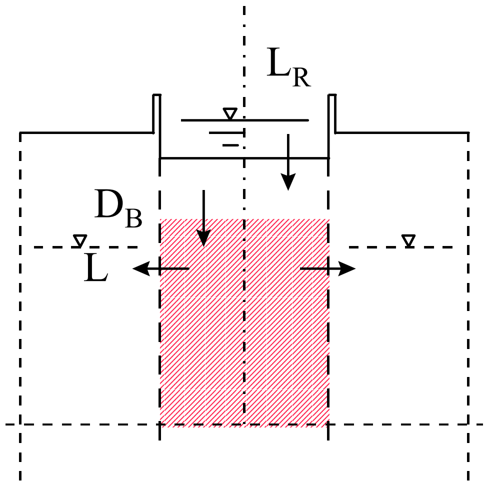

Figure 4-10. Recharge can occur when the basin has water

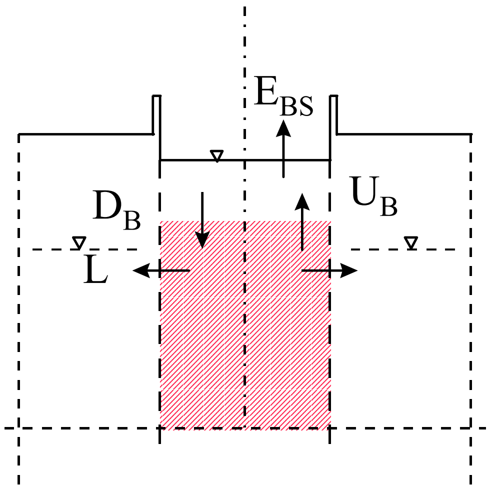

Figure 4-11. Both recharge and upflow can occur when the basin is dry

To determine D_B , the same mechanism as that of farm recharge in section 3.3 on page 14 is used. The same principle is used to estimate upflow U_B as in section 3.4 on page 16. However, there are two small modifications.

Firstly, for the bare soil situation at the basin bottom, there is no crop root zone. So in equation (3-17) in page 16, Z_R becomes the distance from the soil surface to the water table, that is water table depth (T_G). Equation (3-18) on page 17 is transformed to:

$$Z_R = |T_G| \qquad (4\text{-}13)$$

Secondly, when using equation (3-20) on page 18 to calculate normalised soil water content x, another water content limit to replace lower limit of plant available water (θ_L) is required. As stated in section 0 on page 24, when the soil is very dry and its water content reaches a low critical value (θ_{DRY}), its evaporation approaches zero. At this time, there is also no upflow from the water table. Thus θ_{DRY} replaces θ_L and equation (3-20) is changed to:

$$x = \frac{\theta_{ST} - \overline{\theta}}{\theta_{ST} - \theta_{DRY}} \qquad (4\text{-}14)$$

5. Interchange Between Basin and Farmland

5.1 Basic Principles

Interchange (L, mm/d) between basin and farm is a process of water exchange through their interface. Interchange can occur through shallow lateral leakage and through the vertical soil boundary between the farm and basin. In reality, this interchange would include both unsaturated and saturated water flow. This model simplifies the interchange to the flow pattern shown in Figure 5-1. L is driven by the head difference between the farmland and basin soil. Water tables in the farm (H_F) and basin (H_B) are approximated as horizontal. The rate of L is estimated using Darcys' Law:

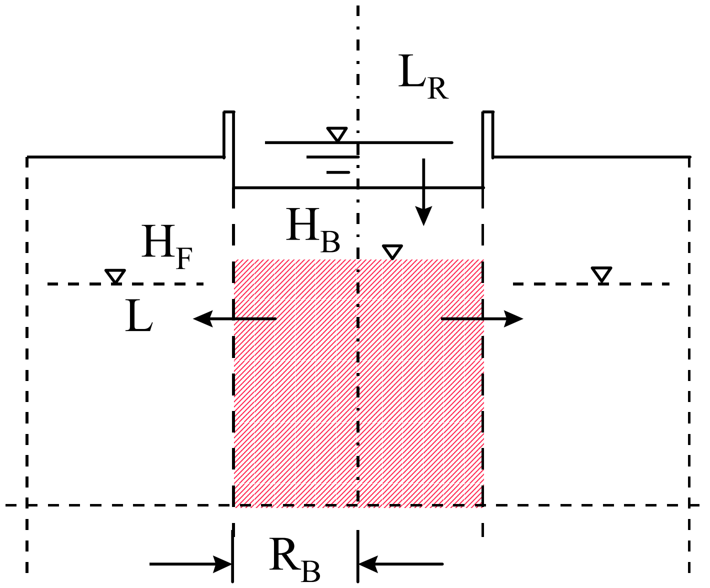

Figure 5-1. Schematic diagram for interchange between basin and farm

$$L = 1000 \times K_{SF} \times (H_B - H_F)/R_B \qquad (5\text{-}1)$$

Where K_{SF} : saturated hydraulic conductivity of soil in the farm (m/d)

R_B : average distance from the centre of basin to farm (m)

If R_B is approximated as the radius of a circle with basin area A_B , then:

$$A_B = \pi R_B^2 \qquad (5\text{-}2)$$

L is measured in mm/d. The volumetric rate of interchange flow (Q_L , m^3/d) is calculated by multiplying the flux L by the perpendicular area intersecting the basin and the farm:

$$Q_L = 0.001 \times L \times 2\,\pi R_B \times H_{DM} \qquad (5\text{-}3)$$

Substituting for L gives:

$$Q_L = K_{SF} \times 2\,\pi H_{DM} \times (H_B - H_F) \qquad (5\text{-}4)$$

This is an approximation as it is assumed that the height of the area interfacing the farm and the basin is equal to the total height of the study domain from the underlying aquitard to the farm natural surface (H_{DM}). In reality this height would be from the water table at the farm/basin interface to the underlying aquitard. Therefore this assumption will lead to an over estimate of the volume of interchange, especially when the water table is very low. However the systems of interest are those where the water table is approaching the natural surface, in these cases this assumption is considered reasonable.

In terms of hydraulic connection between basin and farm, interchange L plays the exchange role. For any time step Δt, L is firstly estimated from the information at the beginning of Δt, then mass balance calculations for both sides can be done separately.

5.2 Further Flux Controls

The exchange between the basin and farmland needs some extra controls to prevent any unrealistic results as outlined below. If the basin water table (H_B) is higher than that in the farm (H_F), there will be a flow from basin to farm ($L > 0$). This flow will increase the farm water table and establish a new level (H_{FM}). This flow will also decrease the water basin table and establish a new level (H_{BM}). Obviously, the new farm water table (H_{FM}) can not exceed the new basin water table (H_{BM}). However, due to the discretisation of continuous processes in a numerical simulation, unrealistic results may sometimes occur, as illustrated in Figure 5-2 and Figure 5-3.

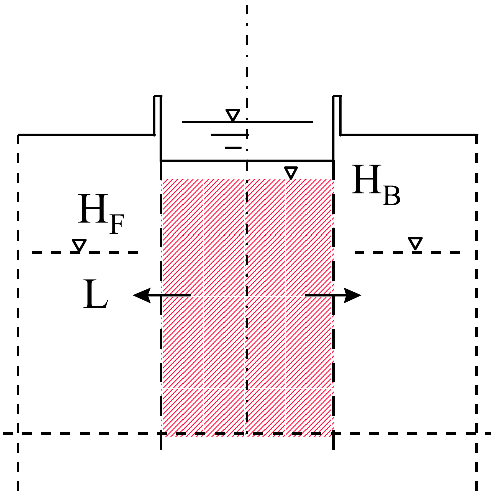

Figure 5-2. Interchange $L>0$ when $H_B > H_F$

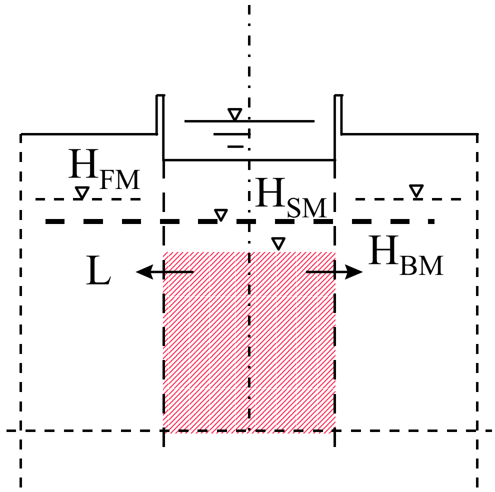

Figure 5-3. Unrealistic result of $H_{FM} > H_{BM}$

These unrealistic water tables may also occur when flow is in the opposite direction, Figure 5-4 and Figure 5-5.

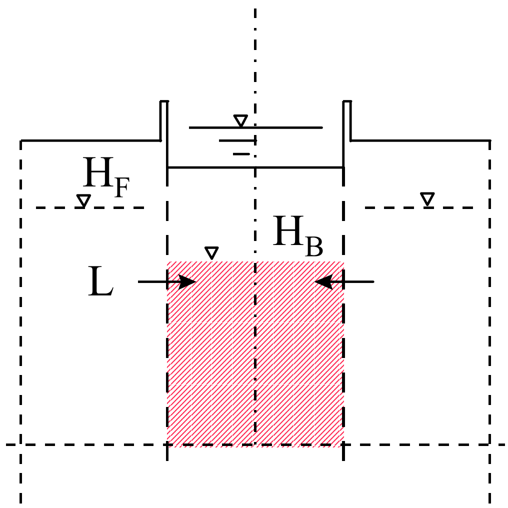

Figure 5-4. Interchange $L<0$ when $H_F > H_B$

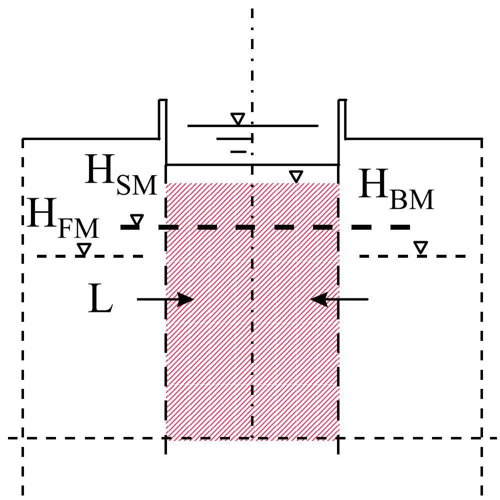

Figure 5-5. Unrealistic result of $H_{BM} > H_{FM}$

If unrealistic cases as in Figure 5-3 or Figure 5-5 occur, the water table in farm and basin should be the same (H_{SM}) by conservation of energy. In light of this, the interchange L that is initially obtained from Darcys' Law (equation (5-1), page 31) needs to be modified. The logic process for this is described as follows:

1. If $L > 0$, there is a flux from basin to farm. Considering L only,

$$H_B \downarrow, \Rightarrow \text{ calculate new level } H_{BM} \tag{5-5}$$

$$H_F \uparrow, \Rightarrow \text{ calculate new level } H_{FM} \tag{5-6}$$

§ If $H_{BM} > H_{FM}$, L is reasonable and accepted

§ Else if $H_{BM} < H_{FM}$, L is unreasonable, then

$\Rightarrow$ calculate the same level H_{SM} and adjust L (5-7)

2. Else if $L < 0$, there is a flux from farm to basin. Considering L only,

$H_F \downarrow$, $\Rightarrow$ calculate new level H_{FM} (5-8)

$H_B \uparrow$, $\Rightarrow$ calculate new level H_{BM} (5-9)

§ If $H_{FM} > H_{BM}$, L is reasonable and accepted

§ Else if $H_{FM} < H_{BM}$, L is unreasonable, then

$\Rightarrow$ calculate the same level H_{SM} and adjust L (5-10)

5.3 Model Execution

In this model, at the start of a time step Δt , the farm can be either saturated or unsaturated, that is farm water table $H_F(t)$ can be either $= 0$ or < 0. The basin soil also can be either saturated or unsaturated. The basin water table can be either higher or lower than the basin bottom (H_{BB}), that is $H_B(t) > H_{BB}$ (in this case $H_B(t)$ is equal to the water level in the basin) or $H_B(t) < H_{BB}$. Only considering L from Darcys' Law, at the end of Δt , both the water table in farm $H_F(t + \Delta t)$ and basin soil $H_B(t + \Delta t)$ have all the same possibilities as the start of Δt. This model also allows the basin bottom level to be higher than the farm surface, so such a combination of water tables in both farm and basin is possible at both the beginning and the end of Δt .

Following is an example to show how L is calculated in the case of $L < 0$ as in Figure 5-4 and Figure 5-5.

$L < 0$, water table in farm drops, water content of soil previously below the water table drops from saturation (θ_{ST}) to field capacity (θ_{FC}). Thus, farm water table (H_{FM}) is described by:

$$(H_{FM} - H_F(t)) \times A_F \times (\theta_{ST} - \theta_{FC}) = 0.001 \times L \times A_B \qquad (5\text{-}11)$$

Rearranging,

$$H_{FM} = H_F(t) + 0.001 \times L \times A_B / (A_F \times (\theta_{ST} - \theta_{FC})) \qquad (5\text{-}12)$$

To determine H_{BM} , there are the following possibilities:

1. If $H_B(t) < H_{BB}$, then

This means the basin soil is unsaturated. Since $L < 0$, the basin water table will rise. Firstly it is assumed that the new level (H_{BM}) will still stay below the basin bottom, i. e. in the soil. H_{BM} fulfils the equation:

$$(H_{BM} - H_B(t)) \times A_B \times (\theta_{ST} - \theta_B) = -0.001 \times L \times A_B \qquad (5\text{-}13)$$

Where θ_B is the average water content in the unsaturated zone of basin soil. Thus:

$$H_{BM} = H_B(t) - 0.001 \times L / (\theta_{ST} - \theta_B) \qquad (5\text{-}14)$$

§ However, if $H_{BM} > H_{BB}$, then

Above assumption of $H_{BM} < H_{BB}$ is not correct. H_{BM} needs to be recalculated. That means H_{BM} will exceed basin bottom:

$$(H_{BM} - H_{BB}) \times A_B + (H_{BB} - H_B(t)) \times A_B \times (\theta_{ST} - \theta_B) = -0.001 \times L \times A_B \qquad (5\text{-}15)$$

$$H_{BM} = -0.001 \times L + H_{BB} + (H_{BB} - H_B(t)) \times (\theta_{ST} - \theta_B) \qquad (5\text{-}16)$$

2. Else if $H_B(t) > H_{BB}$, then

The basin soil is saturated. H_{BM} will be higher than basin bottom H_{BB} , H_{BM} meets:

$$(H_{BM} - H_B(t)) \times A_B = -0.001 \times L \times A_B \qquad (5\text{-}17)$$

$$H_{BM} = -0.001 \times L + H_B(t) \qquad (5\text{-}18)$$

After the above calculations, the acceptability of the results is checked. If $H_{FM} > H_{BM}$, the result is reasonable and Darcy Law flux L is accepted. Otherwise, the result needs to be modified, as shown in Figure 5-5. Following is an example of how the result is modified when $H_F(t) < H_{BB}$.

If $H_F(t) < H_{BB}$, then

See Figure 5-4, obviously, $H_B(t) < H_{BB}$. The same level (H_{SM}) that both farm and basin soil must reach is between $H_F(t)$ and $H_B(t)$. H_{SM} follows the relationship:

$$(H_F(t) - H_{SM}) \times A_F \times (\theta_{ST} - \theta_{FC}) = (H_{SM} - H_B(t)) \times A_B \times (\theta_{ST} - \theta_B) \qquad (5\text{-}19)$$

Thus,

$$H_{SM} = \frac{H_F(t) \times A_F \times (\theta_{ST} - \theta_{FC}) + H_B(t) \times A_B \times (\theta_{ST} - \theta_B)}{A_F \times (\theta_{ST} - \theta_{FC}) + A_B \times (\theta_{ST} - \theta_B)} \qquad (5\text{-}20)$$

The modified and finally accepted L can be calculated by the following equation:

$$L = -1000 \times (H_{SM} - H_B(t)) \times (\theta_{ST} - \theta_B) \qquad (5\text{-}21)$$

By using the same principles, no matter whether $L > 0$ or $L < 0$, all other possibilities can be dealt with

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6. Farm Water Balance

6.1 Principles

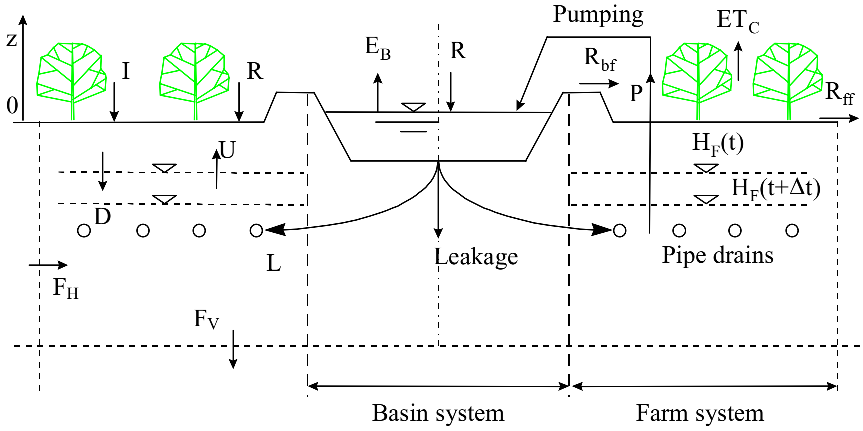


Figure 6-1. Conceptual diagram for farm water balance

In the schematic the datum is taken as the soil surface, above this being positive and below negative For a time step Δt, the water balance equation is:

$$W_F(t + \Delta t) = W_F(t) + I + R + L + R_{BF} - P - ET_C + F_C - F_G - F_V \qquad (6\text{-}1)$$

Where

$W_F(t)$: farm soil water storage at the start of Δt . The depth of model domain reflects the local hydrogeology, typically for the MIA 30m is adequate.

$W_F(t + \Delta t)$: farm soil water storage at the end of Δt

R_{BF} : basin overflow

R_{FF} : farm runoff, occurs if soil profile is completely saturated.

The above water balance equation will not indicate water table changes, to do this the unsaturated and saturated zone need to be considered separately.

Water balance for unsaturated soil zone in farm is:

$$\Delta W_{FU}(t) = I + R + R_{BF} + U_F - ET_C - D_F \quad (6\text{-}2)$$

$$W_{FU}(t + \Delta t) = W_{FU}(t) + \Delta W_{FU}(t) \quad (6\text{-}3)$$

Where

$\Delta W_{FU}(t)$: increment of soil water storage in the unsaturated zone during Δt

$W_{FU}(t)$: soil water storage in unsaturated zone at the start of Δt

$W_{FU}(t + \Delta t)$: soil water storage in unsaturated zone at the end of Δt

U_F : upflow from water table to unsaturated zone

D_F : recharge from unsaturated zone to water table

The water balance equation for the saturated soil zone in the farm is:

$$\Delta W_{FS}(t) = L + D_F - P - U_F + F_C - F_G - F_V \quad (6\text{-}4)$$

$$W_{FS}(t + \Delta t) = W_{FS}(t) + \Delta W_{FS}(t) \quad (6\text{-}5)$$

Where

$\Delta W_{FS}(t)$: increment of soil water storage in saturated zone during Δt

$W_{FS}(t)$: soil water storage in saturated zone at the start of Δt

$W_{FS}(t + \Delta t)$: soil water storage in saturated zone at the end of Δt

Water table variation is a continuous process, when using numerical methods to simulate this for a discrete time step some simplifications are made:

- Firstly equation (6-2) and (6-4) are used for balance calculations while water tables are considered to be constant;
- Secondly, the average water content of soil in the unsaturated zone at the end of Δt ($\theta_F(t + \Delta t)$) is calculated;
- Water table change is considered to occur instantaneously at the end of Δt. Water table movement up or down is controlled by the sign (+ or –) of increment soil water storage in the saturated zone $\Delta W_{FS}(t)$. The magnitude is decided by both $\theta_F(t + \Delta t)$ and $\Delta W_{FS}(t)$.

There are the following expressions to simulate water table $H_F(t + \Delta t)$ in the farm:

$$\Rightarrow \text{ calculate } \Delta W_{FU}(t) \text{ and } \Delta W_{FS}(t) \tag{6-6}$$

$$\theta_F(t + \Delta t) = (W_{FU}(t) + \Delta W_{FU}(t))/\left| H_F(t) \right| \tag{6-7}$$

If $\Delta W_{FS}(t) > 0$, the water table will rise and water will fill part of the soil porosity above the original water table position from $\theta_F(t + \Delta t)$ to saturation θ_{ST} . Otherwise, if $\Delta W_{FS}(t) < 0$, the water table will fall and part of the soil below the original water table will drain from saturation to $\theta_F(t + \Delta t)$.

$$\Delta H_F(t) = \Delta W_{FS}(t)/(\theta_{ST} - \theta_F(t + \Delta t)) \tag{6-8}$$

$$H_F(t + \Delta t) = H_F(t) + \Delta H_F(t) \tag{6-9}$$

Using $\theta_F(t + \Delta t)$ and $H_F(t + \Delta t)$, the water stored in the soil can be calculated for both the unsaturated and saturated zone at the end of Δt :

$$W_{FU}(t + \Delta t) = \theta_F(t + \Delta t) \times \left| H_F(t + \Delta t) \right| \tag{6-10}$$

$$W_{FS}(t + \Delta t) = \theta_{ST} \times (H_F(t + \Delta t) - H_{DM}) \tag{6-11}$$

Where, H_{DM} is the depth of the study domain.

$W_{FU}(t + \Delta t)$ and $W_{FS}(t + \Delta t)$ are used as the values for the beginning of the next time step. It is worth mentioning that equations (6-3) and (6-5) are not used to calculate the water tables as they do not consider the water table variation.

The principles explained in this section are generalisations. Actual situations and model calculations are more complicated than these. For example, there are normally two soil zones in the farm, but when the farm is totally saturated, there is only one. This model covers all the possible soil water conditions, the process of deriving a farm water balance is explained below.

6.2 Model Simulation When an Unsaturated Soil Zone Exists

In this case the water table in the farm is less than 0 and there exists both an unsaturated and saturated zone which are separated by a phreatic surface. Without considering water table change the farm water balance for the unsaturated soil zone for a one day time step is:

$$\Delta W_{FU}(t) = 0.001 \times (I + R - ET_C + U_F - D_F) \times A_F + R_{BF} \quad (6\text{-}12)$$

$$W_{FU}^* = W_{FU}(t) + \Delta W_{FU}(t) \quad (6\text{-}13)$$

Where: I, R, ET_C , U_F and D_F all are in mm/d. A_F is in m^2. R_{BF} is in m^3/d. W_{FU}^* is a temporary variable to record water stored in the unsaturated zone for the end of this time step without considering water table change. All water storage variables are in m^3.

It should be pointed out that the basin runoff R_{BF} is calculated from the basin water balance which is carried out before the farm water balance in the model.

Similarly, the farm water balance for the saturated soil zone for a one day time step is:

$$\Delta W_{FS}(t) = 0.001 \times (L \times A_B + (D_F - U_F - P) \times A_F) + F_C - F_G - F_V \quad (6\text{-}14)$$

$$W_{FS}^* = W_{FS}(t) + \Delta W_{FS}(t) \quad (6\text{-}15)$$

Where L is in mm/d based on basin area. A_B is in m^2. P is in mm/d based on farm area. F_C , F_G , F_V are in m^3/d. W_{FS}^* is a temporary variable to record water stored in the saturated zone for the end of this time step without considering water table change. All water storage variables are in m^3.

Under natural conditions, soil cannot become totally dry, so the soil water content is always greater than zero, thus the average water content of soil above a water table is greater than a minimum value (θ_{FMN}). θ_{FMN} is a specified input dependent on soil type.

Normally, the soil water content is within the above limits when carrying out the water balance simulation. However under certain conditions such as a thin unsaturated soil layer or due to the limitation of numerical discretisation, the soil water content may vary outside these limits. To keep the soil water content within these reasonable limits, the following processes are adopted:

Firstly the average water content of soil above the water table is examined:

$$\theta_{TS} = W_{FU}^{*}/(A_F \times |H_F(t)|) \qquad (6\text{-}16)$$

If $\theta_{TS} > \theta_{FMN}$, the water balance calculations from equation (6-12) to (6-15) are reasonable and accepted. Otherwise, upflow from the water table is increased until θ_{TS} is equal to θ_{FMN} . Thus:

§ If $\theta_{TS} < \theta_{FMN}$, then

$$W_{FU}^{*} = \theta_{FMN} \times A_F \times |H_F(t)| \qquad (6\text{-}17)$$

Based upon equation (6-12) and (6-13), we get

$$U_F = 1000 \times (W_{FU}^{*} - W_{FU}(t) - R_{BF})/A_F + ET_C + D_F - I - R \qquad (6\text{-}18)$$

Now the farm water balance for the saturated soil zone is adjusted:

$$\Delta W_{FS}(t) = 0.001 \times (L \times A_B + (D_F - U_F - P) \times A_F) + F_C - F_G - F_V \qquad (6\text{-}19)$$

$$W_{FS}^{*} = W_{FS}(t) + \Delta W_{FS}(t) \qquad (6\text{-}20)$$

After examining the average water content of soil above the water table, the water table variation during the time step is determined. The water storage in the whole soil profile at the end of Δt (W_F^{*}, m^3) without considering runoff is:

$$W_F^{*} = W_{FU}^{*} + W_{FS}^{*} \qquad (6\text{-}21)$$

Note that W_F^{*} can also be directly obtained from equation (6-1).

In terms of soil water distribution, firstly the soil profile is filled to complete saturation after which runoff will occur. The runoff amount is the excess water after profile saturation. The model does not consider water ponding above the farm surface. The maximum water storage (W_{FMX} , m^3) in the farm soil profile is:

$$W_{FMX} = \theta_{ST} \times A_F \times |H_{DM}| \quad (6\text{-}22)$$

There are two possibilities for W_F^*.

1. If $W_F^* > W_{FMX}$, then

Water balance results can be easily acquired as follows:

$$\theta_F(t + \Delta t) = \theta_{ST} \quad \text{(soil is saturated)} \quad (6\text{-}23)$$

$$H_F(t + \Delta t) = 0 \quad \text{(water table reaches soil surface)} \quad (6\text{-}24)$$

$$W_{FU}(t + \Delta t) = 0 \quad \text{(unsaturated layer disappears)} \quad (6\text{-}25)$$

$$W_{FS}(t + \Delta t) = W_{FMX} \quad \text{(total soil water storage is filled)} \quad (6\text{-}26)$$

$$R_{FF} = W_F^* - W_{FMX} \quad \text{(runoff occurs)} \quad (6\text{-}27)$$

2. Else if $W_F^* < W_{FMX}$, then

There exists an unsaturated soil zone. The average soil water content $\theta_F(t + \Delta t)$ for this zone is calculated and the water balance derived depending upon its magnitude.

$$\theta_F(t + \Delta t) = W_{FU}^* / (A_F \times |H_F(t)|) \quad (6\text{-}28)$$

§ If $\theta_F(t + \Delta t) < \theta_{ST}$, then

The soil remains unsaturated. The water table variation ($\Delta H_F(t)$, m) during Δt and $H_F(t + \Delta t)$ are:

$$\Delta H_F(t) = \Delta W_{FS}(t) / (A_F \times (\theta_{ST} - \theta_F(t + \Delta t))) \quad (6\text{-}29)$$

$$H_F(t + \Delta t) = H_F(t) + \Delta H_F(t) \quad (6\text{-}30)$$

§ Else if $\theta_F(t + \Delta t) > \theta_{ST}$, then

This is a special situation and the average water content of the unsaturated soil is assumed to be field capacity (θ_{FC}).

$$\theta_F(t + \Delta t) = \theta_{FC} \tag{6-31}$$

Thus $H_F(t + \Delta t)$ is determined from:

$$\theta_{FC} \times A_F \times (0 - H_F(t + \Delta t)) + \theta_{ST} \times A_F \times (H_F(t + \Delta t) - H_{DM}) = W_F^* \tag{6-32}$$

Viz:

$$H_F(t + \Delta t) = (W_F^*/A_F + \theta_{ST} \times H_{DM})/(\theta_{ST} - \theta_{FC}) \tag{6-33}$$

Model execution has shown that on rare occasions $\theta_F(t + \Delta t)$ from equation (6-28) is approximately equal to θ_{ST} and thus $\theta_{ST} - \theta_F(t + \Delta t)$ approaches to zero. So when using equation (6-29), a small $\Delta W_{FS}(t)$ causes a large $\Delta H_F(t)$. This results in a very rapid change of the water table $H_F(t)$. This is unlikely when compared with empirical evidence of water table variation. The reason for this simulation problem is that when the soil profile is not wholly saturated, the upper limit that the average soil water content of the unsaturated zone can reach is set by θ_{ST} .

To overcome this, the upper limit can be reduced from θ_{ST} to a slightly lower critical level (θ_{CR}). θ_{CR} can be represented as:

$$\theta_{CR} = R_\theta \times \theta_{ST} \tag{6-34}$$

Where the ratio R_θ is set as 0.95. In practical terms this is not unreasonable since soil with a with high water content has the tendency to drain and raise the water table rather than to maintain a high moisture content above a deeper water table. This adaptation using θ_{CR} is more stable than using θ_{ST} alone.

The simulation processes including the above factors are as below:

§ If $\theta_F(t + \Delta t) < \theta_{CR}$, then

$$\Delta H_F(t) = \Delta W_{FS}(t)/(A_F \times (\theta_{ST} - \theta_F(t + \Delta t))) \tag{6-35}$$

$$H_F(t+\Delta t) = H_F(t) + \Delta H_F(t) \quad (6\text{-}36)$$

§ Else if $\theta_F(t+\Delta t) > \theta_{CR}$, then

$$\theta_F(t+\Delta t) = \theta_{FC} \quad (6\text{-}37)$$

$$H_F(t+\Delta t) = (W_F^*/A_F + \theta_{ST}\times H_{DM})/(\theta_{ST} - \theta_{FC}) \quad (6\text{-}38)$$

So, when $W_F^* < W_{FMX}$, water storage of soil for both unsaturated and saturated zone at the end of Δt are:

$$W_{FU}(t+\Delta t) = \theta_F(t+\Delta t)\times \left| H_F(t+\Delta t) \right| \times A_F \quad (6\text{-}39)$$

6.3 Model Simulation when there is no Unsaturated Zone

In this case the farm water table is at the soil surface, there is no unsaturated zone. Using the same principles as in the unsaturated case, the water balance is done as follows:

$$\Delta W_{FU}(t) = 0 \quad (6\text{-}40)$$

$$\Delta W_{FS}(t) = 0.001\times (I + R - ET_C - P)\times A_F + 0.001\times L\times A_B + R_{BF} + F_C - F_G - F_V \quad (6\text{-}41)$$

1. If $\Delta W_{FS}(t) > 0$, then

$$\theta_F(t+\Delta t) = \theta_{ST} \quad \textit{(soil is saturated)} \quad (6\text{-}42)$$

$$H_F(t+\Delta t) = 0 \quad \textit{(water table is at soil surface)} \quad (6\text{-}43)$$

$$W_{FU}(t+\Delta t) = 0 \quad \textit{(unsaturated layer disappears)} \quad (6\text{-}44)$$

$$W_{FS}(t+\Delta t) = W_{FMX} \quad \textit{(total storage is filled)} \quad (6\text{-}45)$$

$$R_{FF} = \Delta W_{FS}(t) \quad \textit{(runoff occurs)} \quad (6\text{-}46)$$

2. Else if $\Delta W_{FS}(t) < 0$, then

An unsaturated zone will emerge at the end of Δt. The average water content of this zone will be field capacity (θ_{FC}).

$$\theta_F(t + \Delta t) = \theta_{FC} \quad (6\text{-}47)$$

According to this scenario, we have

$$\Delta H_F(t) = \Delta W_{FS}(t)/(A_F \times (\theta_{ST} - \theta_{FC})) \quad (6\text{-}48)$$

$$H_F(t + \Delta t) = \Delta H_F(t) \quad (6\text{-}49)$$

$$W_{FU}(t + \Delta t) = \theta_F(t + \Delta t) \times \left| H_F(t + \Delta t) \right| \times A_F \quad (6\text{-}50)$$

$$W_{FS}(t + \Delta t) = \theta_{ST} \times (H_F(t + \Delta t) - H_{DM}) \times A_F \quad (6\text{-}51)$$

7. Basin Water Balance

Generally, the principles used to establish water balances for the basin system are similar to those used for the farm system, however the basin system has two different bodies, the open water body in the basin and the soil body below the basin.

For a time step Δt, taking the whole basin system as an entity, the water balance equation is:

$$W_{BW}(t + \Delta t) = W_{BW}(t) + P + R - E_B - L \qquad (7\text{-}1)$$

Where

$W_{BW}(t)$:	water stored in the whole basin system at the start of Δt. The depth of the model domain is the same as that for the farm.
$W_{BW}(t + \Delta t)$:	water stored in whole basin system at the end of Δt.
E_B	basin evaporation, this can be open water evaporation or soil evaporation.

Overflow from the basin (R_{BF}) can occur in extreme circumstances. It is determined by comparing the water level in the basin (H_R) with the highest possible water level (H_{RE}) at which the basin is totally full. According to section 3.5, H_{RE} is the sum of the maximum allowable water level in the basin (H_{RA}) and the basin free board (F_B). Thus:

$$H_{RE} = H_{RA} + F_B \qquad (7\text{-}2)$$

- If $H_R(t + \Delta t) > H_{RE}$, then

$$R_{BF} = H_R(t + \Delta t) - H_{RE} \qquad (7\text{-}3)$$

7.1 Water Balance For Open Water In The Basin

The following equation is used to describe the status of the basin for a 1 day time step:

$$H_{RM} = 1000 \times H_R(t) + P \times (A_F / A_B) + R \qquad (7\text{-}4)$$

Where H_{RM} is in mm, $H_R(t)$ in m. P is in mm/d based on farm area. R is in mm/d.

If $H_{RM} = 0$, there is no water in the basin, thus open water evaporation from the basin (E_{BR}) and ponded water leakage from the basin into the soil below (L_R) are all equal to zero. In this case the basin bottom (S_{BD}) is an evaporation boundary.

$$E_{BR} = 0 \qquad (7\text{-}5)$$

$$L_R = 0 \qquad (7\text{-}6)$$

$$S_{BD} = \text{'EVAPORATION'} \qquad (7\text{-}7)$$

$$E_{SS} = E_W \qquad (7\text{-}8)$$

Where

S_{BD} : a variable to flag the boundary condition at the basin bottom. If the boundary is infiltrating, then S_{BD} = *'INFILTRATION'*. Basin boundary information is required in setting up water balances for the basin soil.

E_{SS} : potential evaporation rate from basin bottom when the soil is saturated (mm/d)

If $H_{RM} > 0$, there is water in the basin . Both E_{BR} and L_R may exist. Firstly assuming there is continually water in the basin, then possible evaporation (E_{PS} , mm/d) is set to open water evaporation (E_W) and possible leakage (L_{PS} , mm/d) is calculated.

$$E_{PS} = E_W \qquad (7\text{-}9)$$

Potential leakage from the basin L_{PS} is related to the soil water status below the basin which is represented by the variable S_{FM} . If the soil is saturated, then S_{FM} = *'SATURATED'*; otherwise S_{FM} = *'UNSATURATED'*.

1. If $S_{FM}(t)$ = *'SATURATED'* , then

L_{PS} can be determined as in section 4.3.1 on page 26. At this stage discharge from the soil into the basin is not considered.

$$\text{Assumed basin leakage } L_R^* = 1000 \times K_{SB} \qquad [7\text{-}10]$$

§ If $L > 0$ and $L_R^* > L$, then

$$L_{PS} = L \quad \textit{(leakage is controlled by the basin to farm flux)} \qquad [7\text{-}11]$$

§ Else if $L > 0$ and $L_R^* < L$, then

$$L_{PS} = L_R^* \quad \textit{(leakage is controlled by the basin bottom layer)} \qquad [7\text{-}12]$$

§ Else if $L < 0$, then

$$L_{PS} = 0 \qquad [7\text{-}13]$$

2. Else if $S_{FM}(t)$ = *'UNSATURATED'* , then

LPS is estimated using the methods described in section 4.3.2, page 27. For simplicity the saturated hydraulic conductivity of soil at the basin bottom is used for illustration:

$$L_{PS} = 1000 \times K_{SB} \qquad [7\text{-}14]$$

Based upon the above, actual evaporation and leakage in the basin can be determined and then the water balance calculated.

1. If $(H_{RM} - E_{PS} - L_{PS}) > 0$, then

There is enough water to maintain open water evaporation and leakage from the water body in the basin during Δ t. The basin bottom is an infiltration boundary. Thus:

$$E_{BR} = E_{PS} \quad (7\text{-}15)$$

$$L_R = L_{PS} \quad (7\text{-}16)$$

$$S_{BD} = \text{'INFILTRATION'} \quad (7\text{-}17)$$

2. Else if $(H_{RM} - E_{PS} - L_{PS}) < 0$, then

There is not enough water to maintain E_{PS} and L_{PS} simultaneously. In this case, for simplicity it is assumed the water in the basin will firstly meet the open water evaporation demand and then the rest will infiltrate into the soil.

§ If $(H_{RM} - E_{PS}) > 0$, then

$$E_{BR} = E_{PS} \quad (7\text{-}18)$$

$$L_R = H_{RM} - E_{PS} \quad (7\text{-}19)$$

$$S_{BD} = \text{'INFILTRATION'} \quad (7\text{-}20)$$

§ Else if $(H_{RM} - E_{PS}) < 0$, then

$$E_{BR} = H_{RM} \quad (7\text{-}21)$$

$$L_R = 0 \quad (7\text{-}22)$$

$$S_{BD} = \text{'EVAPORATION'} \quad (7\text{-}23)$$

$$E_{SS} = E_W - H_{RM} \quad (7\text{-}24)$$

E_{BR} has used the assigned amount of water H_{RM} . So in equation (7-24), E_{SS} is reduced accordingly.

The water level in the basin at the end of Δt is obtained by:

$$H_R(t + \Delta t) = H_R(t) + 0.001 \times (P \times (A_F / A_B) + R - E_{BR} - L_R) \qquad (7\text{-}25)$$

7.2 Water Balance for Basin Soil in Saturation

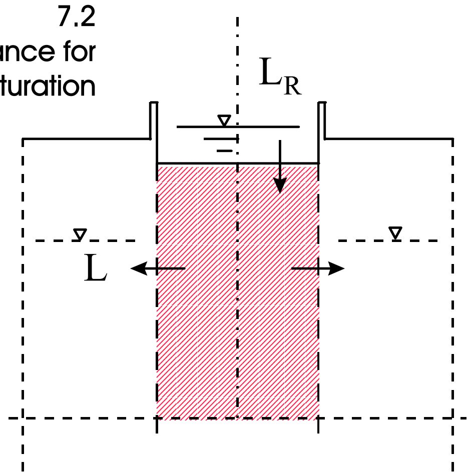


Figure 7-1. Infiltration boundary

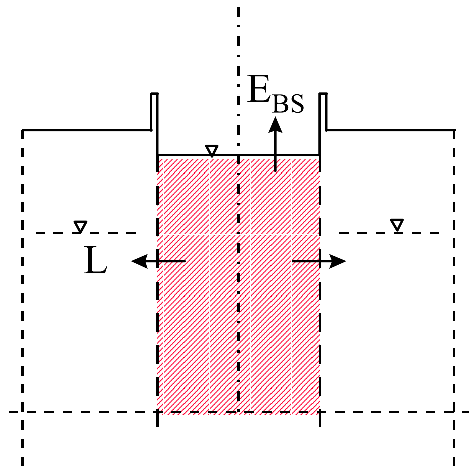


Figure 7-2. Evaporation boundary

As shown in Figure 7-1 and Figure 7-2, two cases can occur when the basin soil is saturated.

For an infiltration boundary as in Figure 7-1, the water balance equation is:

$$W_B(t + \Delta t) = W_B(t) + L_R - L \qquad (7\text{-}26)$$

Where

$W_B(t)$:	water stored in the whole basin soil (excluding basin storage) at the beginning of Δt
$W_B(t + \Delta t)$:	water stored in the whole basin soil at the end of Δt

For an evaporation boundary as in Figure 7-2, the water balance equation is:

$$W_B(t + \Delta t) = W_B(t) - E_{BS} - L \qquad (7\text{-}27)$$

In terms of programming, below are the specific expressions for a Δt:

§ If S_{BD} = 'INFILTRATION', then

$$W_B^* = W_B(t) + 0.001 \times A_B \times (L_R - L) \quad (7\text{-}28)$$

§ Else if S_{BD} = 'EVAPORATION', then

$$W_B^* = W_B(t) - 0.001 \times A_B \times (E_{BS} + L) \quad (7\text{-}29)$$

Where, W_B^* is a temporary variable to record water storage in the whole basin soil profile at the end of Δt without considering overflow from the soil. All water storage variables are in m^3. L_R , L, E_{BS} all are in mm/d. A_B is in m^2.

The soil water distribution is considered similarly to the farm water balance. Water firstly stays in the soil profile, then if the soil profile is completely saturated overflow will occur. This overflow is discharge from the basin soil into the basin as free water as illustrated in section 4.3, page 25. The maximum water storage (W_{BMX} , m^3) in basin soil profile is:

$$W_{BMX} = \theta_{ST} \times A_B \times (H_{BB} - H_{DM}) \quad (7\text{-}30)$$

There are two possibilities with W_B^*.

1. If $W_B^* > W_{BMX}$, then

This can occur when $L < 0$. Discharge into the basin storage will increase the water level in it. Water balance results are obtained as follows:

$$D_R = 1000 \times (W_B^* - W_{BMX})/A_B \quad (7\text{-}31)$$

$$H_R(t + \Delta t) = H_R(t + \Delta t) + 0.001 \times D_R \quad (7\text{-}32)$$

$$H_B(t + \Delta t) = H_{BB} + H_R(t + \Delta t) \quad (7\text{-}33)$$

$$\theta_B(t + \Delta t) = \theta_{ST} \quad (7\text{-}34)$$

$$S_{FM}(t + \Delta t) = \text{'SATURATED'} \quad (7\text{-}35)$$

$$W_B(t+\Delta t) = W_{BMX} \qquad (7\text{-}36)$$

$$W_{BU}(t+\Delta t) = 0 \qquad (7\text{-}37)$$

$$W_{BS}(t+\Delta t) = W_{BMX} \qquad (7\text{-}38)$$

In equation (7-33) the water table in the basin soil (H_B) is equal to the open water level in the basin. In equation (7-37) and (7-38), W_{BU} and W_{BS} are the soil water storage in the unsaturated and saturated zone, respectively, of the basin profile.

2. Else if $W_B^* < W_{BMX}$, then

An unsaturated zone will be present at the end of Δt, the average water content of which will be field capacity (θ_{FC}).

$$\theta_B(t+\Delta t) = \theta_{FC} \qquad (7\text{-}39)$$

Thus the water in the basin soil $H_B(t+\Delta t)$ can be derived from the equation:

$$\theta_{FC}\times(H_{BB}-H_B(t+\Delta t))\times A_B + \theta_{ST}\times(H_B(t+\Delta t)-H_{DM})\times A_B = W_B^* \qquad (7\text{-}40)$$

Water balance results are as follows:

$$H_B(t+\Delta t) = (W_B^*/A_B-\theta_{FC}\times H_{BB} + \theta_{ST}\times H_{DM})/(\theta_{ST}-\theta_{FC}) \qquad (7\text{-}41)$$

$$S_{FM}(t+\Delta t) = \text{'UNSATURATED'} \qquad (7\text{-}42)$$

$$W_B(t+\Delta t) = W_B^* \qquad (7\text{-}43)$$

$$W_{BU}(t+\Delta t) = \theta_B(t+\Delta t)\times(H_{BB}-H_B(t+\Delta t))\times A_B \qquad (7\text{-}44)$$

$$W_{BS}(t+\Delta t) = \theta_{ST}\times(H_B(t+\Delta t)-H_{DM})\times A_B \qquad (7\text{-}45)$$

7.3 Water Balance for Basin when Soil is Unsaturated

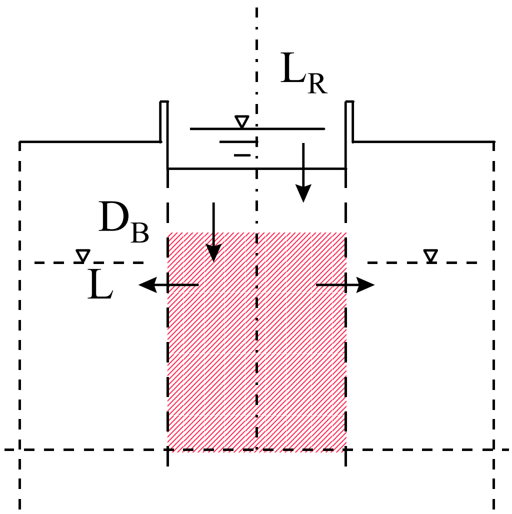


Figure 7-3. Infiltration boundary

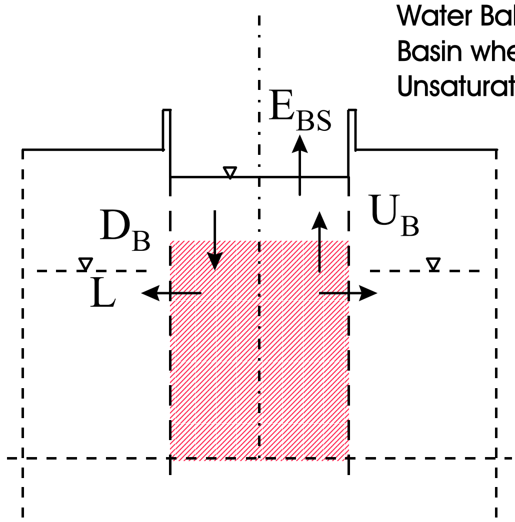


Figure 7-4. Evaporation boundary

Figure 7-3 and Figure 7-4 show the two situations that can occur when the basin soil has an unsaturated layer. Because there exists an unsaturated zone, the model execution for these situations is similar to that for the farm water balance in section 6.2, page 40. The conceptual water balance equations for both unsaturated and saturated zones are:

For an infiltration boundary as in Figure 7-3, the water balance is given by:

$$W_{BU}(t+\Delta t) = W_{BU}(t) + L_R - D_B \tag{7-46}$$

$$W_{BS}(t+\Delta t) = W_{BS}(t) + D_B - L \tag{7-47}$$

For an evaporation boundary as in Figure 7-4, the water balance is given by:

$$W_{BU}(t+\Delta t) = W_{BU}(t) + U_B - E_{BS} - D_B \tag{7-48}$$

$$W_{BS}(t+\Delta t) = W_{BS}(t) + D_B - U_B - L \tag{7-49}$$

In terms of programming, below are the specific expressions for a Δt:

1. If S_{BD} = *'INFILTRATION'*, then

$$W_{BU}^{*} = W_{BU}(t) + 0.001 \times A_B \times (L_R - D_B) \quad (7\text{-}50)$$

$$W_{BS}^{*} = W_{BS}(t) + 0.001 \times A_B \times (D_B - L_R) \quad (7\text{-}51)$$

Where, W_{BU}^{*} and W_{BS}^{*} are temporary variables to record water storage in the unsaturated and saturated zone respectively at the end of Δt without considering any water table change in the basin soil. All water storage variables are in m^3.

2. Else if S_{BD} = *'EVAPORATION'*, then

$$W_{BU}^{*} = W_{BU}(t) + 0.001 \times A_B \times (U_B - E_{BS} - D_B) \quad (7\text{-}52)$$

Similarly to the farm soil there is a minimum water content for basin soil above a water table (θ_{BMN}). The need for this mechanism can be illustrated by examining an extreme condition. If θ_B becomes equal to θ_{DRY} , then E_{BS} is equal to *0*. Upflow is also driven by evaporation and thus becomes zero. Since the drained upper limit θ_{DUL} is greater than θ_{DRY} , then drainage D_B becomes zero. From equation (7-52), water storage doesn't change and θ_B still has the value of θ_{DRY} . In light of this analysis:

$$\theta_{BMN} = \theta_{DRY} \quad (7\text{-}53)$$

Theoretically, θ_B can not be less than θ_{BMN} , but under certain conditions such as a very thin unsaturated layer, the numerical simulation may cause θ_B to become less than θ_{BMN} . If this occurs, the average water content of the soil above the water table is examined:

$$\theta_{TS} = W_{BU}^{*} / (A_B \times (H_{BB} - H_B(t))) \quad (7\text{-}54)$$

If $\theta_{TS} > \theta_{BMN}$, then the water balance calculation from equation (7-52) is reasonable and accepted. Otherwise, upflow from the water table is used to increase θ_{TS} up to θ_{BMN} . Thus:

§ If $\theta_{TS} < \theta_{BMN}$, then

$$W_{BU}^{*} = \theta_{BMN} \times A_B \times (H_{BB} - H_B(t)) \quad (7\text{-}55)$$

Based upon equation (6-12) and (6-13):

$$U_B = 1000\times(W_{BU}^{*} - W_{BU}(t))/A_B + E_{BS} + D_B \qquad (7\text{-}56)$$

Thus under an evaporation boundary condition, the water balance for the saturated zone is:

$$W_{BS}^{*} = W_{BS}(t) + 0.001\times A_B\times(D_B - U_B - L) \qquad (7\text{-}57)$$

Under an infiltration boundary condition, θ_B drops to θ_{DUL} and then drainage D_B becomes zero. Thus the water balance calculation from equation (7-50) can not result in θ_B less than θ_{BMN} and there is no need to examine θ_B .

From the above simulations for both infiltration and evaporation boundaries, water storage in the whole basin soil profile at the end of Δt without considering overflow from the soil (W_B^{*}) is:

$$W_B^{*} = W_{BU}^{*} + W_{BS}^{*} \qquad (7\text{-}58)$$

By comparing W_B^{*} with W_{BMX} , there are two possibilities.

1. If $W_B^{*} > W_{BMX}$, then

This can occur when $L < 0$. Discharge into the basin storage will increase water level in it. The water balance is as follows:

$$D_R = 1000\times(W_B^{*} - W_{BMX})/A_B \qquad (7\text{-}59)$$

$$H_R(t+\Delta t) = H_R(t+\Delta t) + 0.001\times D_R \qquad (7\text{-}60)$$

$$H_B(t+\Delta t) = H_{BB} + H_R(t+\Delta t) \qquad (7\text{-}61)$$

$$\theta_B(t+\Delta t) = \theta_{ST} \qquad (7\text{-}62)$$

$$S_{FM}(t+\Delta t) = \text{'SATURATED'} \qquad (7\text{-}63)$$

$$W_B(t+\Delta t) = W_{BMX} \tag{7-64}$$

$$W_{BU}(t+\Delta t) = 0 \tag{7-65}$$

$$W_{BS}(t+\Delta t) = W_{BMX} \tag{7-66}$$

2. Else if $W_B^* < W_{BMX}$, then

An unsaturated soil zone still exists. Water balance calculations are conducted according to the magnitude of the average soil water content $\theta_B(t+\Delta t)$:

$$\theta_B(t+\Delta t) = W_{BU}^*/(A_B \times (H_{BB} - H_B(t))) \tag{7-67}$$

- If $\theta_B(t+\Delta t) < \theta_{CR}$, then

This is the normal situation. The water table variation ($\Delta H_B(t)$, m) during Δt and other balance results are:

$$\Delta H_B(t) = (W_{BS}^* - W_{BS}(t))/(A_B \times (\theta_{ST} - \theta_B(t+\Delta t))) \tag{7-68}$$

$$H_B(t+\Delta t) = H_B(t) + \Delta H_B(t) \tag{7-69}$$

$$S_{FM}(t+\Delta t) = \text{'UNSATURATED'} \tag{7-70}$$

$$W_B(t+\Delta t) = W_B^* \tag{7-71}$$

$$W_{BU}(t+\Delta t) = \theta_B(t+\Delta t) \times (H_{BB} - H_B(t+\Delta t)) \times A_B \tag{7-72}$$

$$W_{BS}(t+\Delta t) = \theta_{ST} \times (H_B(t+\Delta t) - H_{DM}) \times A_B \tag{7-73}$$

§ Else if $\theta_B(t+\Delta t) > \theta_{CR}$, then

This is a special situation. The average water content of the unsaturated soil is set to field capacity (θ_{FC}).

$$\theta_B(t+\Delta t) = \theta_{FC} \tag{7-74}$$

Thus the water table in the basin soil $H_B(t+\Delta t)$ can be derived from the equation:

$$\theta_{FC}\times(H_{BB}-H_B(t+\Delta t))\times A_B + \theta_{ST}\times(H_B(t+\Delta t)-H_{DM})\times A_B = W_B^* \tag{7-75}$$

Water balance results are as follows:

$$H_B(t+\Delta t) = (W_B^*/A_B-\theta_{FC}\times H_{BB} + \theta_{ST}\times H_{DM})/(\theta_{ST}-\theta_{FC}) \tag{7-76}$$

$$S_{FM}(t+\Delta t) = \text{'UNSATURATED'} \tag{7-77}$$

$$W_B(t+\Delta t) = W_B^* \tag{7-78}$$

$$W_{BU}(t+\Delta t) = \theta_B(t+\Delta t)\times(H_{BB}-H_B(t+\Delta t))\times A_B \tag{7-79}$$

$$W_{BS}(t+\Delta t) = \theta_{ST}\times(H_B(t+\Delta t)-H_{DM})\times A_B \tag{7-80}$$

After conducting the water balance calculations for the basin soil either saturated or unsaturated, it can be determined whether basin overflow will occur. According to equation (7-3):

§ If $H_R(t+\Delta t) < H_{RE}$, then

$$R_{BF} = 0 \tag{7-81}$$

§ Else if $H_R(t+\Delta t) > H_{RE}$, then

$$R_{BF} = A_B\times(H_R(t+\Delta t)-H_{RE}) \tag{7-82}$$

$$H_R(t+\Delta t) = H_{RE} \tag{7-83}$$

Similarly the basin soil water table $H_B(t + \Delta t)$ should also be confined:

§ If $H_B(t + \Delta t) > (H_{RE} + H_{BB})$, then

$$H_B(t + \Delta t) = H_{RE} + H_{BB} \quad (7\text{-}84)$$

It can be seen that this confinement is necessary only when the basin soil is saturated.

8. Inputs and Outputs

8.1 General Outlines

To run this model, the following basic information on both the farm and basin system is required:

1. Geometric data such as the farm area (A_F) and basin area (A_B), position of the basin bottom (H_{BB}) relative to ground level and depth of aquitard below farm surface (domain depth H_{DM});

2. Meteorological data on a daily basis:

    § potential evapotranspiration (ET_0);

    § open water evaporation coefficient (K_W) to calculate open water evaporation from ET_0 ;

    § rainfall (R);

3. Crop data:

    § crop coefficients (K_C) to derive crop water use from ET_0 ;

    § root zone thickness (D_{RZ});

4. Soil hydraulic properties:

    § saturated hydraulic conductivity of the soil in the farm (K_{SF});

    § saturated hydraulic conductivity of the soil at the basin bottom (K_{SB});

    § water retention curve of the soil $\theta(\psi)$;

    § threshold water table depth below which upflow would be less than 1mm/d (Z_{max});

5. Irrigation management data:

    § maximum allowable water deficit (D_{WC});

    § irrigation efficiency (C_I);

6. Drainage system data:

    § drain spacing (L_D), depth to the drains (W), thickness of the impermeable substratum below the drains (D), maximum drainage rate of the drainage system (C_{PD});

§ saturated hydraulic conductivity of soil above the drains (K_1), saturated hydraulic conductivity of soil below the drains (K_2) which should be the same as the farm conductivity (K_{SF});

7. Waterlogging management data:

§ allowable water table limit in farmland to prevent waterlogging (H_{FA});

§ allowable water level in basin storage to prevent overflow (H_{RA});

8. Water content indices:

§ saturated water content of the soil (θ_{ST});

§ field capacity (θ_{FC});

§ critical water content of the basin soil when surface evaporation becomes zero (θ_{DRY});

§ lower limit of plant available water (θ_L);

§ drained upper limit (θ_{DUL}), same as field capacity;

§ minimum water content of farm soil above water table (θ_{FMN});

§ minimum water content of basin soil above water table (θ_{BMN});

9. Initial physical conditions of the system:

§ initial water table and water content of the soil in the farm;

§ initial water depth in the basin storage;

§ initial basin soil conditions ('*SATURATED*' or '*UNSATURATED*') and accordingly water content and water table in the basin soil.

From the water balance calculation, results are obtained as follows:

1. Daily water balance components in the farm:

§ crop evapotranspiration (ET_C);

§ irrigation (I);

§ recharge from the unsaturated zone to the water table (D_F);

§ upflow from the water table to the unsaturated zone (U_F);

§ pumping from the drainage system (P);

§ runoff (R_{FF});

§ water table height (H_F);

§ average water content of the soil in the unsaturated zone (θ_F);

2. Daily water balance components of the basin storage:
    - § open water evaporation (E_{BR});
    - § leakage through bottom (L_R);
    - § overflow (R_{BF});
    - § depth of water (H_R);
3. Daily water balance components of soil below the basin:
    - § soil evaporation (E_{BS});
    - § recharge from unsaturated zone to water table (D_B);
    - § upflow from water table to unsaturated zone (U_B);
    - § water table height (H_B);
    - § average water content of soil in the unsaturated zone (θ_B);
4. Daily water balance component between the farm and basin:
    - § interchange (L).

Water table heights are important outputs of the model. To assist in assessing the effects of model scenarios on the farm water tables, some further analysis of the results is provided:

- § number of days the farm water table is above any given limit;
- § number of days when waterlogging occurs;
- § number of days when the basin is dry;
- § number of days when the basin has some water;
- § number of days when the basin is full ($H_R = H_{RA}$);
- § number of days the basin water level is above any given height.

This analysis can be undertaken over a whole year or any part or parts of a year as specified by the user.

8.2 Input Data File Construction

To assist in understanding the construction of the input data file, the variable names used in the computer model are used for illustration. Table 8-1 to Table 8-4 are 4 examples of the input data information used to run the model. The description of the input data follows the order of the data file. Each title in the list below corresponds to a group of inputs required.

1. ISGC, NWTL, NTPD

ISGC: number of water table upper limits (H_{FA}) used to control pumping (integer);

NWTL: number of water table depths used to assess the farm water table condition (integer);

NTPD: number of time periods in one year for which the farm water table assessment is carried out (integer).

Thus the model allows variable water table control limits during the growing, this is useful if a crop is more prone to waterlogging stress at certain times and thus a deeper water table is required at those times. The water table assessment can be provided for any time period of particular interest to the user and for any particular water table depth..

2. JPHL, JBPD

JPHL: number of pond water heights selected to assess pond water status (integer);

JBPD: number of time periods in one year for which pond water status assessment is carried out (integer).

Thus the basin water status can be assessed in terms of how full the basin is over the whole year or for certain periods.

3. FBSYSTEM, BASINBTM

FBSYSTEM: disposal options for the farm subsurface drainage. This can be given the following values:

- 'ONFARM' meaning normal on-farm evaporation basins;
- 'F+PUMPING' meaning farm only with pumping discharge to the outside environment (no basin). If the maximum capacity of the subsurface drainage system (C_{PD}) is set to zero, then the model can simulate the farm without any pumping.
- Development of the model in the future may allow 'OUTFARM' meaning the farm drainage is disposed of into an evaporation basin outside the farm system. This will be useful for analysis of community basins.

BASINBTM: options for the hydraulic properties of the basin bottom. This variable can be:

- 'NOLINING' meaning the normal leakage conditions encountered with a basin;
- 'LINING' meaning the basin bottom is lined, no leakage is allowed.

4. JOBAIM

JOBAIM: the purpose of this simulation. This can be:

- 'SIMULATION' which is to obtain simulation results for one given farm and basin area;
- 'OPTIMIZATION' which offers the user the opportunity to complete multiple program executions using different inputs of basin area to farm area ratio. The resulting output provides a relationship between basin to farm area ratio, and water table depth. This relationship enables the user to decide on an appropriate ratio of basin to farm area for the intended basin application.

4(1). NSETB

NSETB: number of sets of farm and basin areas for comparison (integer).

Thus, it can be seen that NSETB = 1 if JOBAIM = 'SIMULATION'.

5. METEFILE, OUTFILE

METEFILE: name of the meteorological data file, this file should have firstly a column with reference ET and then a column for rainfall on a daily basis;

OUTFILE: name of the output file where the model results are stored.

6. (ABSETHA(I), I=1, NSETB)

(AFSETHA(I), I=1, NSETB)

ABSETHA: array to store basin areas (ha);

AFSETHA: array to store farm areas (ha).

7. UPBANK, RLWBAS, PWHMAX

UPBANK: height of the allowable water level in the basin (m) to prevent overflow in subsequent time steps;

RLWBAS: height of the basin bottom (m);

PWHMAX: maximum allowable depth of water (m) in the basin (H_{RA}).

Heights are positive upward with datum at the farm soil surface. The relationship: PWHMAX = UPBANK – RLWBAS must be fulfilled.

8. RKSBA, RKSEX

RKSBA: saturated hydraulic conductivity of soil (m/day) at the basin bottom which is used to calculate the leakage from the basin into basin soil (K_{SB}). If the basin bottom is lined, RKSBA should be input as zero.

RKSEX: saturated hydraulic conductivity of soil (m/day) around the basin which is used to calculate the interchange between the basin and farm. RKSEX is normally given the value of the farm soil (K_{SF}) unless conditions under the basin are quite different.

9. ALAY, GTABIN, THETAIN

ALAY: depth (m) of the study domain for water balance (H_{DM});

GTABIN: initial water table depth in the farm (m);

THETAIN: initial water content of soil above the farm water table (v/v).

10. STCFMIN

STCFMIN: initial salt content in the farm groundwater. This is assigned as zero as this model does not have a salt balance at present.

11. THEST, THEFC, THELL, THEDRY, PAWLL, THEBUC, THEMNF, THEMNB, RATHE

THEST: saturated water content of the soil (θ_{ST}) (v/v);

THEFC: field capacity (θ_{FC}) (v/v);

THELL: allowable lower limit of the farm soil water content when a soil water content index is used to manage irrigation (v/v);

THEDRY: critical water content of the basin soil when evaporation becomes zero (θ_{DRY}) (v/v);

PAWLL: lower limit of plant available water (θ_L) (v/v);

THEBUC: drained upper limit (θ_{DUL}) for recharge calculation, the same value as THEFC (v/v);

THEMNF: minimum water content of the farm soil above water table (θ_{FMN}) (v/v);

THEMNB: minimum water content of the basin soil above water table (θ_{BMN}) (v/v);

RATHE: ratio of the upper limit water content that the unsaturated soil can reach when there exists an unsaturated zone above water table (θ_{CR}) to θ_{ST} , see equation (6-34).

All the above soil water contents are volumetric.

12. AUP, BUP, CUP, ZROOT, ZUPMAX

AUP: regression coefficient used in the upflow equation (3-17) (a);

BUP: regression coefficient used in the upflow equation (3-17) (b);

CUP: regression coefficient used in the upflow equation (3-17) (c);

ZROOT: crop root zone thickness (m) (D_{RZ});

ZUPMAX: threshold water table depth (m) below which upflow would be less than 1mm/d (Z_{max}).

13. IRCONT

IRCONT is the way in which irrigation is managed. IRCONT can be either

'SOILWAT' meaning irrigation is controlled by farm soil water content; or

'ET+RAIN' meaning irrigation is controlled by meteorological conditions.

It should be noted that managing irrigation using the soil water content index was preliminarily tested in the model, however the results were unsatisfactory. The inclusion of this option here is for possible further improvement of the model in this area. Managing irrigation by meteorological conditions has proven to be satisfactory and is thus adopted in the model.

a. IF(IRCONT .EQ. 'SOILWAT') THEN

13(1). IRWAY

IRWAY: method to determine each irrigation amount. IRWAY can be

§ 'ASSIGNED' meaning irrigation is an assigned amount of water;

§ 'SUITABLE' meaning irrigation is managed by a soil water content index;

§ 'EXCESSIVE' meaning a certain depth of soil is saturated at each irrigation.

IF(IRWAY .EQ. 'ASSIGNED') THEN

13(2). AMIRR

AMIRR: the assigned irrigation amount (mm);

- ELSE IF(IRWAY .EQ. 'SUITABLE') THEN

CONTINUE

ELSE IF(IRWAY .EQ. 'EXCESSIVE') THEN

13(2). TOPSAT

TOPSAT: the depth of soil to be saturated (m).

b. ELSE IF(IRCONT .EQ. 'ET+RAIN') THEN

13(1). WATDEF, EFFIRR

WATDEF: maximum allowable water deficit (D_{WC}) (mm);

EFFIRR: irrigation efficiency (C_I), this value is the ratio of the irrigation water applied and the actual deficit, typical values are in **Error! Reference source not found.**.

14. RKSFA, ALPHA

RKSFA: saturated hydraulic conductivity (m/day) of the farm soil (K_{SF});

ALPHA: exponential empirical index in Gardner equation (3-11) (α).

15. P1, P2, P3, P4

P1, P2, P3, P4: parameters in Van Genuchten's water retention curve, typical values are in Table 3-2.

16. COWAEV

COWAEV: open water evaporation coefficient (K_W), it is suggested that this value can range from 0.8 for large water bodies (~100ha) to 1- 1.1 for small water bodies 1 to 5 ha in area.

17. (CPCOMON(I), I=1, 12)

CPCOMON: array to store monthly average crop coefficients (K_C). If required, K_C can be input on a daily basis.

18. BASLEV

BASLEV: method by which evaporation from the basin soil is to be determined when the basin is dry. BASLEV can be:

- 'LINEAR' meaning the basin soil evaporation is simulated by a linear relationship discussed in section 0;
- 'MET+COEF' meaning the basin soil evaporation is simulated by using crop coefficients for a fallow soil.

IF(BASLEV .EQ. 'MET+COEF') THEN

18(1). (CPFAMON(I), I=1, 12)

CPFAMON: array to store monthly average crop coefficients for a fallow.

19. DEPDR, SPACING, BIGD, SMU

DEPDR: depth (m) to the drains (W);

SPACING: drain spacing (L_D) (m);

BIGD: depth (m) to the impermeable substratum below the drains (D);

SMU: wet entry perimeter (m) for the drain (u), usually about 0.3.

20. RKS1, RKS2

RKS1: saturated hydraulic conductivity (m/day) of the soil above drains (K_1);

RKS2: saturated hydraulic conductivity (m/day) of the soil below drains (K_2).

These two hydraulic conductivities are used in Hooghoudt drainage formulae (3-24), which normally have the value of the saturated hydraulic conductivity for the farm soil (K_{SF}). Note that the inputs in sections 19, 20 and 22 should be related in an appropriate manner.

21. (IDBC(I), MBC(I), IDEC(I), MEC(I), GTUPV(I), I=1, ISGC)

IDBC: start day of each farm water table height set to control the pumping regime (H_{FA}) (integer);

MBC: start month of each H_{FA} (integer);

IDEC: last day of each H_{FA} (integer);

MEC: last month of each H_{FA} (integer);

GTUPV: farm water table heights set for controlling pumping (H_{FA}).

22. TILEMAX, TIEXDAY

TILEMAX: maximum capacity (mm/day) of the subsurface drainage system (C_{PD}) to discharge water, this is controlled by pipe and pump sizing;

TIEXDAY: period of time used to determine the depth of freeboard required in the basin (F_B) in equation (3-21), a one day minimum is required to prevent overflow.

23. (WTASS(I), I=1, NWTL)

WTASS: water table depths used to assess the farm water table conditions.

24. (NTDB(I), NTMB(I), NTDE(I), NTME(I), I=1, NTPD)

NTDB: start day of each time period in one year when farm water table analysis is conducted (integer);

NTMB: start month of each time period (integer);

NTDE: last day of each time period (integer);

NTME: last month of each time period (integer).

25. (BHASS(I), I=1, JPHL)

BHASS: pond water heights selected to assess pond water status (m).

26. (JBDB(I), JBMB(I), JBDE(I), JBME(I), I=1, JBPD)

JBDB: start day of each time period in a year when basin water height analysis is conducted (integer);

JBMB: start month of each time period (integer);

JBDE: last day of each time period (integer);

JBME: last month of each time period (integer).

27. UNSINFMD

UNSINFMD: method to determine the leakage from the basin into basin soil when it is unsaturated. UNSINFMD can be:

§ 'SIMPLE' meaning the leakage is simply the saturated hydraulic conductivity of soil at the basin bottom (K_{SB});

§ 'GREEN-AMPT' meaning the leakage is estimated using the Green-Ampt infiltration model.

IF(UNSINFMD .EQ. 'GREEN-AMPT') THEN

27(1). ZFTMOD, RLIM, FLIM

ZFTMOD: method by which the wetting front (Z_{WF}) is to be determined. ZFTMOD can be:

§ 'ESTIMATION' meaning approximately estimating Z_{WF} without solving the wetting front equation;

§ 'RATIO' meaning obtaining Z_{WF} by using the proportional root seeking method to solve the wetting front equation;

§ 'BINARY' meaning obtaining Z_{WF} by using the binary cutting method to solve the wetting front equation. This method is recommended when using the Green-Ampt infiltration model to estimate basin leakage.

RLIM: maximum allowable error for roots when solving the wetting front equation;

FLIM: maximum allowable error for the root equation when solving the wetting front equation. When the absolute value of the root equation is less than FLIM, it is regarded to be equal to zero.

28. BASOIL(1,1)

BASOIL: array to record the soil water status below the basin (S_{FM}). BASOIL(1,1) is the initial status of the basin soil. It can be:

§ 'SATURATED';

§ 'UNSATURATED'.

29. BADEPIN, STCBAIN

BADEPIN: initial water depth (m) in the basin;

STCBAIN: initial salt concentration of water in the basin, not used at present.

IF(BASOIL(1,1) .EQ. 'UNSATURATED') THEN

29(1). THEBAS(1,1), GTBAS(1,1)

THEBAS: array to record average water content in unsaturated zone of the basin soil (θ_B) (v/v). THEBAS(1,1) is the initial value.

GTBAS: array to record water table height (m) in the basin soil (H_B). GTBAS(1,1) is the initial value.

When BASOIL(1,1) .EQ. 'SATURATED', THEBAS(1,1) is equal to the saturated soil water content (θ_{ST}) and GTBAS(1,1) is at the basin water level. So in this situation, this is no need to input these two quantities.

30. PFADAY, PBADAY, LGDAY

PFADAY: control variable to output daily water balance results for the farm when the JOBAIM .EQ. 'SIMULATION':

- § 'YES' meaning results are output;
- § 'NO' meaning results are not output.

PBADAY: control variable to output daily water balance results for the basin when the JOBAIM .EQ. 'SIMULATION':

- § 'YES' meaning results are output;
- § 'NO' meaning results are not output.

LGDAY: control variable to output daily water balance results for the whole system for graphing when JOBAIM .EQ. 'SIMULATION':

- § 'YES' meaning results are output;
- § 'NO' meaning results are not output.

Outputs from the model are shown and analysed in the next few chapters.

Table 8-1. Input data sheet for a typical simulation job

1	ISGC	NWTL	NTPD						
	01	07	01						
2	JPHL	JBPD							
	07	01							
3	FBSYSTEM	BASINBTM							
	'ONFARM'	'NOLINING'							
4	JOBAIM								
	'SIMULATION'								
5	METEFILE	OUTFILE							
	'GRF62-96'	'S075I1.1'							
6	(ABSETHA(I), I=1, NSETB)								
	(AFSETHA(I), I=1, NSETB)								
	1.5								
	20.0								
7	UPBANK	RLWBAS	PWHMAX						
	0.5	-0.5	1.0						
8	RKSBA	RKSEX							
	0.0015	0.2							
9	ALAY	GTABIN	THETAIN						
	-30.0	-1.5	0.3						
10	STCFMIN								
	0.0								
11	THEST	THEFC	THELL	THEDRY	PAWLL	THEBUC	THEMNF	THEMNB	RATHE
	0.42	0.35	0.3	0.15	0.2	0.35	0.2	0.15	0.95
12	AUP	BUP	CUP	ZROOT	ZUPMAX				
	3.92759	3.78835	0.50794	1.0	1.5				
13	IRCONT								
	'ET+RAIN'								
13(1)	WATDEF	EFFIRR							
	25.0	1.15							
14	RKSFA	ALPHA							
	0.2	2.0							
15	P1	P2	P3	P4					
	0.32	186.441	0.86	0.1					
16	COWAEV								
	0.85								
17	(CPFAMON(I), I=1, 12)								
	2*0.6	7*0.7	3*0.6						
18	BASLEV								
	'LINEAR'								
19	DEPDR	SPACING	BIGD	SMU					
	-2.0	30.0	4.0	0.3					
20	RKS1	RKS2							
	0.2	0.2							
21	(IDBC(I), MBC(I), IDEC(I), MEC(I), GTUPV(I), I=1, ISGC)								
	01	01	31	12	-1.5				
22	TILEMAX	TIEXDAY							
	5.0	1.0							
23	(WTASS(I), I=1, NWTL)								
	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.5		
24	(NTDB(I), NTMB(I), NTDE(I), NTME(I), I=1, NTPD)								
	01	01	31	12					
25	(BHASS(I), I=1, JPHL)								
	1.0E-6	0.2	0.4	0.5	0.6	0.8	1.0		
26	(JBDB(I), JBMB(I), JBDE(I), JBME(I), I=1, JBPD)								
	01	01	31	12					
27	UNSINFMD								
	'SIMPLE'								
28	BASOIL(1,1)								
	'SATURATED'								
29	BADEPIN	STCBAIN							
	0.5	0.0							
30	PFADAY	PBADAY	LGDAY						
	'NO'	'NO'	'YES'						

Table 8-2. Input data sheet for a typical optimization job

1	ISGC	NWTL	NTPD												
	01	07	01												
2	JPHL	JBPD													
	07	01													
3	FBSYSTEM	BASINBTM													
	'ONFARM'	'NOLINING'													
4	JOBAIM														
	'**OPTIMIZATION**'														
4(1)	**NSETB**														
	15														
5	METEFILE	OUTFILE													
	'GRF62-96'	'S075I1.1'													
6	(ABSETHA(I), I=1, NSETB)														
	(AFSETHA(I), I=1, NSETB)														
	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	2.0	2.5	3.0	3.5	4.0	4.5	5.0
	15*20.0														
7	UPBANK	RLWBAS	PWHMAX												
	0.5	-0.5	1.0												
8	RKSBA	RKSEX													
	0.0015	0.2													
9	ALAY	GTABIN	THETAIN												
	-30.0	-1.5	0.3												
10	STCFMIN														
	0.0														
11	THEST	THEFC	THELL	THEDRY	PAWLL	THEBUC	THEMNF	THEMNB	RATHE						
	0.42	0.35	0.3	0.15	0.2	0.35	0.2	0.15	0.95						
12	AUP	BUP	CUP	ZROOT	ZUPMAX										
	3.92759	3.78835	0.50794	1.0	1.5										
13	IRCONT														
	'ET+RAIN'														
13(1)	WATDEF	EFFIRR													
	25.0	1.15													
14	RKSFA	ALPHA													
	0.2	2.0													
15	P1	P2	P3	P4											
	0.32	186.441	0.86	0.1											
16	COWAEV														
	0.85														
17	(CPFAMON(I), I=1, 12)														
	2*0.6	7*0.7	3*0.6												
18	BASLEV														
	'LINEAR'														
19	DEPDR	SPACING	BIGD	SMU											
	-2.0	30.0	4.0	0.3											
20	RKS1	RKS2													
	0.2	0.2													
21	(IDBC(I), MBC(I), IDEC(I), MEC(I), GTUPV(I), I=1, ISGC)														
	01	01	31	12	-1.5										
22	TILEMAX	TIEXDAY													
	5.0	1.0													
23	(WTASS(I), I=1, NWTL)														
	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.5								
24	(NTDB(I), NTMB(I), NTDE(I), NTME(I), I=1, NTPD)														
	01	01	31	12											
25	(BHASS(I), I=1, JPHL)														
	1.0E-6	0.2	0.4	0.5	0.6	0.8	1.0								
26	(JBDB(I), JBMB(I), JBDE(I), JBME(I), I=1, JBPD)														
	01	01	31	12											
27	UNSINFMD														
	'SIMPLE'														
28	BASOIL(1,1)														
	'SATURATED'														
29	BADEPIN	STCBAIN													
	0.5	0.0													
30	PFADAY	PBADAY	LGDAY												
	'NO'	'NO'	'YES'												

Table 8-3. Input data sheet for a simulation job with lining at the basin bottom and basin soil unsaturated

1	ISGC	NWTL	NTPD						
	01	07	01						
2	JPHL	JBPD							
	07	01							
3	FBSYSTEM	BASINBTM							
	'ONFARM'	**'LINING'**							
4	JOBAIM								
	'SIMULATION'								
5	METEFILE	OUTFILE							
	'GRF62-96'	'S075I1.1'							
6	(ABSETHA(I), I=1, NSETB)								
	(AFSETHA(I), I=1, NSETB)								
	1.5								
	20.0								
7	UPBANK	RLWBAS	PWHMAX						
	0.5	-0.5	1.0						
8	RKSBA	RKSEX							
	0.0	0.2							
9	ALAY	GTABIN	THETAIN						
	-30.0	-1.5	0.3						
10	STCFMIN								
	0.0								
11	THEST	THEFC	THELL	THEDRY	PAWLL	THEBUC	THEMNF	THEMNB	RATHE
	0.42	0.35	0.3	0.15	0.2	0.35	0.2	0.15	0.95
12	AUP	BUP	CUP	ZROOT	ZUPMAX				
	3.92759	3.78835	0.50794	1.0	1.5				
13	IRCONT								
	'ET+RAIN'								
13(1)	WATDEF	EFFIRR							
	25.0	1.15							
14	RKSFA	ALPHA							
	0.2	2.0							
15	P1	P2	P3	P4					
	0.32	186.441	0.86	0.1					
16	COWAEV								
	0.85								
17	(CPFAMON(I), I=1, 12)								
	2*0.6	7*0.7	3*0.6						
18	BASLEV								
	'LINEAR'								
19	DEPDR	SPACING	BIGD	SMU					
	-2.0	30.0	4.0	0.3					
20	RKS1	RKS2							
	0.2	0.2							
21	(IDBC(I), MBC(I), IDEC(I), MEC(I), GTUPV(I), I=1, ISGC)								
	01	01	31	12	-1.5				
22	TILEMAX	TIEXDAY							
	5.0	1.0							
23	(WTASS(I), I=1, NWTL)								
	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.5		
24	(NTDB(I), NTMB(I), NTDE(I), NTME(I), I=1, NTPD)								
	01	01	31	12					
25	(BHASS(I), I=1, JPHL)								
	1.0E-6	0.2	0.4	0.5	0.6	0.8	1.0		
26	(JBDB(I), JBMB(I), JBDE(I), JBME(I), I=1, JBPD)								
	01	01	31	12					
27	UNSINFMD								
	'SIMPLE'								
28	BASOIL(1,1)								
	'UNSATURATED'								
29	BADEPIN	STCBAIN							
	0.5	0.0							
29(1)	THEBAS(1,1)	GTBAS(1,1)							
	0.3	-4.0							
30	PFADAY	PBADAY	LGDAY						
	'NO'	'NO'	'YES'						

Table 8-4. Input data sheet for a simulation job where basin leakage is estimated using the Green-Ampt infiltration model

1	ISGC	NWTL	NTPD						
	01	07	01						
2	JPHL	JBPD							
	07	01							
3	FBSYSTEM	BASINBTM							
	'ONFARM'	'NOLINING'							
4	JOBAIM								
	'SIMULATION'								
5	METEFILE	OUTFILE							
	'GRF62-96'	'S075I1.1'							
6	(ABSETHA(I), I=1, NSETB)								
	(AFSETHA(I), I=1, NSETB)								
	1.5								
	20.0								
7	UPBANK	RLWBAS	PWHMAX						
	0.5	-0.5	1.0						
8	RKSBA	RKSEX							
	0.0015	0.2							
9	ALAY	GTABIN	THETAIN						
	-30.0	-1.5	0.3						
10	STCFMIN								
	0.0								
11	THEST	THEFC	THELL	THEDRY	PAWLL	THEBUC	THEMNF	THEMNB	RATHE
	0.42	0.35	0.3	0.15	0.2	0.35	0.2	0.15	0.95
12	AUP	BUP	CUP	ZROOT	ZUPMAX				
	3.92759	3.78835	0.50794	1.0	1.5				
13	IRCONT								
	'ET+RAIN'								
13(1)	WATDEF	EFFIRR							
	25.0	1.15							
14	RKSFA	ALPHA							
	0.2	2.0							
15	P1	P2	P3	P4					
	0.32	186.441	0.86	0.1					
16	COWAEV								
	0.85								
17	(CPFAMON(I), I=1, 12)								
	2*0.6	7*0.7	3*0.6						
18	BASLEV								
	'LINEAR'								
19	DEPDR	SPACING	BIGD	SMU					
	-2.0	30.0	4.0	0.3					
20	RKS1	RKS2							
	0.2	0.2							
21	(IDBC(I), MBC(I), IDEC(I), MEC(I), GTUPV(I), I=1, ISGC)								
	01	01	31	12	-1.5				
22	TILEMAX	TIEXDAY							
	5.0	1.0							
23	(WTASS(I), I=1, NWTL)								
	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.5		
24	(NTDB(I), NTMB(I), NTDE(I), NTME(I), I=1, NTPD)								
	01	01	31	12					
25	(BHASS(I), I=1, JPHL)								
	1.0E-6	0.2	0.4	0.5	0.6	0.8	1.0		
26	(JBDB(I), JBMB(I), JBDE(I), JBME(I), I=1, JBPD)								
	01	01	31	12					
27	UNSINFMD								
	'**GREEN-AMPT**'								
27(1)	ZFTMOD		RLIM	FLIM					
	'BINARY'		1.0E-4	1.0E-4					
28	BASOIL(1,1)								
	'SATURATED'								
29	BADEPIN	STCBAIN							
	0.5	0.0							
30	PFADAY	PBADAY	LGDAY						
	'NO'	'NO'	'YES'						

9. Model Evaluation

9.1 Water Balance Examination

In order to check the model for any errors, water balance examinations are conducted for both the farm and basin system. The time periods used are 1 day, 1 month, 1 year and the whole simulation period. The constraint for the numerical calculation is that the water stored in the whole system should be equal to the sum of the water stored in different parts of the system. The water stored in the whole system is directly obtained from the water balance equation for the system, that is equation (6-1) for the farm and (7-1) for the basin.

$$W_F(t+\Delta t) = W_F(t) + I + R + L + R_{BF} - P - ET_C + F_C - F_G - F_V \quad (9\text{-}1)$$

$$W_{BW}(t+\Delta t) = W_{BW}(t) + P + R - E_B - L \quad (9\text{-}2)$$

Where the process quantities such as I, R correspond to their total amount in Δt. $W_F(t+\Delta t)$ *and* $W_{BW}(t+\Delta t)$ *are obtained based on the time period* Δt.

However, water storage items in other parts of the system such as $W_{FU}(t+\Delta t)$, $W_{BU}(t+\Delta t)$ are obtained based on a 1 day time step water balance calculation. Thus, these items correspond to the water storage at the end of the last day of Δt. The purpose of obtaining the water storage of the system and its constituents based on different time scales is to examine if the water quantities derived in these different ways coincide with each other. The required equalities are:

$$\varepsilon = W_F(t+\Delta t) - (W_{FU}(t+\Delta t) + W_{FS}(t+\Delta t)) = 0 \quad (9\text{-}3)$$

$$\varepsilon = W_{BW}(t+\Delta t) - (W_{BU}(t+\Delta t) + W_{BS}(t+\Delta t) + H_R(t+\Delta t) \times A_B) = 0 \quad (9\text{-}4)$$

It has been found that for all the time periods selected (1 day, 1 month, 1 year) and the whole simulation period, the water balance has only minor errors and all the physical quantities are within reasonable ranges. Table 9-1 and Table 9-2 are an example of output files showing the annual water balance for the farm and basin system.

Table 9-1. Yearly water balance for the farm for a 7.5% basin area

NO.	YEAR	DAYS	IRRI	RAIN	ET	UPFL	RECH	PUMP	OVERFB	RLEX	OVERFA	FHRC	FHRG	FVET	FAWAM	FW
			I	R	ET_C	U_F	D_F	P	R_{BF}	L	R_{FF}	F_C	F_G	F_V	W_F	
			(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
															12420	
1	1962	365	866.01	354	1166.5	91.34	72.37	13.33	0	15.27	0	0	0	0	12475.46	
2	1963	365	725.2	524	1180.2	113.3	193.7	138	0	18.89	0	0	0	0	12425.34	
3	1964	366	879.41	401	1207.8	84.66	101.1	65.47	0	26.57	0	0	0	0	12459.02	
4	1965	365	1043.5	351	1299.3	105.5	203.9	128.5	0	21.96	0	0	0	0	12447.75	
5	1966	365	859.58	409	1167.2	90.96	139.1	77.64	0	20	0	0	0	0	12491.46	
6	1967	365	1224.5	197	1323.1	107.6	211.3	127.8	0	20.77	0	0	0	0	12482.77	
7	1968	366	848.88	468	1201.5	97.3	203.2	140.7	0	28.94	0	0	0	0	12486.41	
8	1969	365	564.01	611	1148.4	117.7	111.6	114.3	0	41.55	0	0	0	0	12440.34	
9	1970	365	763.47	459	1171.5	87.78	111.9	70.79	0	29.7	0	0	0	0	12450.23	
10	1971	365	829.92	399	1142	93.05	171.2	105.6	0	7.18	0	0	0	0	12438.72	
11	1972	366	1019.2	278	1216.3	92.81	134.8	56.22	0	12.4	0	0	0	0	12475.81	
12	1973	365	484.57	626	1042.7	92.5	164.5	133.2	0	28.03	0	0	0	0	12438.51	
13	1974	365	331.67	683	1011.9	152.1	187.4	123.7	0	39.22	0	0	0	0	12356.9	
14	1975	365	719.37	390	996.71	89.24	41.02	20.4	0	39.04	0	0	0	0	12488.2	
15	1976	366	620.61	366	965.39	76.36	128.1	78.31	0	4.31	0	0	0	0	12435.42	
16	1977	365	843.52	312	1077.4	83.67	111.7	59.4	0	32.94	0	0	0	0	12487.09	
17	1978	365	413.52	556	932.59	188.6	262.8	155.9	0	20.71	0	0	0	0	12388.8	
18	1979	365	968.55	330	1200.1	99.51	57.6	20.19	0	32.67	0	0	0	0	12499.71	
19	1980	366	984.62	292	1207.2	99.02	178.9	114	0	16.19	0	0	0	0	12471.38	
20	1981	365	747.64	445	1110.3	97.16	163.6	131.9	0	30.03	0	0	0	0	12451.83	
21	1982	365	1077.1	142	1132.9	85.43	141.6	83.6	0	22.8	0	0	0	0	12477.24	
22	1983	365	702.88	429	1047.1	85.78	139	108.6	0	28.33	0	0	0	0	12481.72	
23	1984	366	668.47	473	1106.1	91.86	131.7	85.41	0	39.55	0	0	0	0	12471.18	
24	1985	365	751.63	450	1112.2	97.8	184.5	125.7	0	24.1	0	0	0	0	12458.98	
25	1986	365	784.81	379	1110.4	85.62	117.4	77.13	0	25.4	0	0	0	0	12460.62	
26	1987	365	1017.2	344	1267.5	98.3	175.1	121.8	0	26.67	0	0	0	0	12459.16	
27	1988	366	845.49	483	1252.9	154.7	233.1	150.1	0	27.89	0	0	0	0	12412.5	
28	1989	365	690.94	487	1120.1	237	231	127	0	34.17	0.41	0	0	0	12377.07	
29	1990	365	900.67	405	1201.8	111.2	109.8	88.73	0	42.51	0	0	0	0	12434.69	
30	1991	365	1122.6	260	1279	83.97	133.6	51.71	0	12.41	0	0	0	0	12499	
31	1992	366	492.24	574	1018.3	83	156.4	109.6	0	23.64	0	0	0	0	12460.92	
32	1993	365	516.9	596	1094.9	89.07	130.8	100.4	0	26.67	0	0	0	0	12405.21	
33	1994	365	1244	211	1317.2	96.1	144	54.65	0	9.21	0	0	0	0	12497.5	
34	1995	365	752.87	476	1165.9	99.1	171.6	132.2	0	24.04	0	0	0	0	12452.31	
35	1996	366	840.76	433	1204.2	97.5	135.8	96.04	0	35.18	0	0	0	0	12461.05	
Long term average			804.18	416.9	1148.5	104.5	151	96.8	0	25.4	0.01	0	0	0	12461.05	

Table 9-2. Yearly water balance for the basin system for a 7.5% basin area

NO.	YEAR	DAYS	PUMP	RAIN	EWATER	EVBTOP	EVBAS	EVWAS	RATELK	RLEX	OVERFB	UPBG	DNBG	BWSUM	BAWAU
			P	R	E_{W}	E_{BR}	E_{BS}	E_{B}	L_{R}	L	R_{BF}	U_{B}	D_{B}	W_{BW}	W_{BU}
			(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
														12890	
1	1962	365	177.76	354	1557.2	756.67	325.71	1082.37	275.09	203.6	0	18.63	117.7	12135.83	222.7
2	1963	365	1840.6	524	1574.2	1428.33	43.29	1471.62	505.39	251.9	0	2.73	302.1	12776.92	228.6
3	1964	366	872.98	401	1611.09	1248.93	187.75	1436.67	455.91	354.3	0	12.26	335.2	12259.96	249.9
4	1965	365	1712.7	351	1734.08	1444.14	110.28	1554.42	486	292.8	0	8.38	301.7	12476.45	244
5	1966	365	1035.3	409	1554.14	1151.92	224.31	1376.23	425.86	266.6	0	17.07	239.2	12277.81	228.6
6	1967	365	1704.2	197	1766.13	1420.11	179.8	1599.91	462.63	276.9	0	14.34	245.4	12302.18	300.1
7	1968	366	1875.6	468	1609.39	1502.96	68.5	1571.46	523.08	385.8	0	3.27	414.6	12688.51	196
8	1969	365	1523.3	611	1544.28	1544.28	0	1544.28	547.5	554	0	0	547.7	12724.61	228.9
9	1970	365	943.91	459	1567.91	1303.02	147.18	1450.2	478.5	396	0	9.94	375.7	12281.33	232.8
10	1971	365	1407.8	399	1522.69	946.64	238.91	1185.55	363.57	95.74	0	17.11	61.32	12806.83	358
11	1972	366	749.54	278	1620.95	1172.24	240.93	1413.17	331.76	165.3	0	13.41	163.4	12255.89	289.3
12	1973	365	1776.5	626	1393.92	1329.72	38.71	1368.43	526.5	373.7	0	1.95	407	12916.26	209.9
13	1974	365	1648.7	683	1355.66	1355.66	0	1355.66	547.5	523	0	0	517.1	13369.28	92.9
14	1975	365	272	390	1328.38	1141.17	103.79	1244.96	487.32	520.5	0	7.91	465.4	12265.77	234.4
15	1976	366	1044.1	366	1277.98	718.72	146.16	864.87	312.6	57.5	0	10.28	74.08	12753.48	233.0
16	1977	365	791.94	312	1441.6	1051.75	156.07	1207.81	437.34	439.2	0	13.06	397.6	12210.4	210.9
17	1978	365	2079.2	556	1248.65	1160.39	43.65	1204.04	522	276.1	0	2.38	180.1	13365.37	89.4
18	1979	365	269.2	330	1607.35	1173.58	177.48	1351.06	417.04	435.6	0	11.71	373.3	12177.96	234.3
19	1980	366	1520	292	1613.81	1340.14	128.78	1468.92	467.74	215.9	0	10.54	211.3	12305.06	325.8
20	1981	365	1758.4	445	1488.18	1352.03	75.93	1427.96	520.61	400.4	0	4.07	426.9	12680.06	232.6
21	1982	365	1114.6	142	1515.47	1140.11	195.73	1335.83	449.07	304	0	14.59	268.5	12296.79	312.3
22	1983	365	1447.9	429	1407.52	1271.63	82.79	1354.42	511.5	377.8	0	4.13	401.6	12441.52	231.4
23	1984	366	1138.8	473	1482.06	1212.86	115.3	1328.15	495	527.3	0	10.38	496.4	12197.89	197.8
24	1985	365	1675.8	450	1488.77	1352.77	33.64	1386.42	512.59	321.3	0	2.82	344.6	12616.02	181.1
25	1986	365	1028.4	379	1485.89	1205.85	125.06	1330.9	454.7	338.6	0	11.01	310.6	12353.83	226.1
26	1987	365	1624.1	344	1699.49	1404.14	133.62	1537.76	484.51	355.7	0	10.89	337.7	12428.51	249.9
27	1988	366	2001.5	483	1682.41	1434.78	116.29	1551.07	501.06	371.9	0	9.22	305.4	12990.08	200.8
28	1989	365	1693.8	487	1519.12	1498.13	15.11	1513.24	537	455.6	0	0.71	359.8	13202.1	141.7
29	1990	365	1183	405	1613.56	1613.56	0	1613.56	547.5	566.8	0	0	548.3	12609.81	238.0
30	1991	365	689.48	260	1712.67	874.38	312.11	1186.48	338.58	165.5	0	21.63	131.4	12207.32	233.3
31	1992	366	1461.8	574	1356.69	1228.8	54.31	1283.11	516.71	315.2	0	3.49	346	12644.77	197.2
32	1993	365	1339.1	596	1460.56	1292.04	105.57	1397.6	455.29	355.6	0	6.67	338.1	12826.67	226.4
33	1994	365	728.68	211	1756.95	1100.81	308.25	1409.06	313.51	122.9	0	18.15	97.11	12234.43	282.0
34	1995	365	1762.8	476	1556.6	1435.62	73.42	1509.03	508.5	320.5	0	3.14	351.3	12643.71	241.5
35	1996	366	1280.5	433	1612.54	1491.14	77.84	1568.98	522.58	469.1	0	5.64	457.5	12319.11	245.3
Long term average			1290.7	416.9	1536.22	1259.97	125.32	1385.29	464.06	338.6	0	8.61	321.5	12319.11	245.3

9.2 Analysis of the Physical Processes

Using 35 years of daily meteorological data (ET_0 and R) from the CSIRO Griffith Laboratory, a typical simulation was run. The ratio of basin area to drained area was 7.5%. The crop was citrus and the assumed irrigation system was sprinklers. Irrigation was set at 25 mm of crop transpiration, with an irrigation efficiency of 1.1, i.e. a 10% over application. The soil was a loam with drains spaced every 30 m and 2 m deep, but pumping was stopped once the water table reached 1.5 m deep. The saturated hydraulic conductivity of the soil in the farm was 0.2 m/d and that at the basin bottom was 0.0015m/d. The maximum allowable basin water depth was 1 m, with a freeboard of 0.1 m plus 1 day pumping. The open water evaporation coefficient used was 0.85.

Figure 9-1 is a plot of crop evapotranspiration and the farm water table. The shallow water tables mostly occur in winter with increased rainfall and lower evaporative demand, whereas deeper water tables occur in summer. In this weather sequence the wettest years are 11, 12, 16 and 31, years 11 and 12 being respectively the sixth and second wettest on record. The driest years are 5, 20, 29 and 32, year 20 being the driest ever at Griffith.

Figure 9-2 and Figure 9-3 show that irrigation is in the summer period when crop water consumption is high. The irrigation amount fluctuates around 30mm, the input maximum allowable deficit was 25mm.

Figure 9-4 shows the farm soil water content and depth to water table. The soil water content generally remained at or near field capacity (0.35). Corresponding with periods of high water tables, the soil water content increases to near saturation (0.42). On some occasions in the middle of summer, the soil water content decreased to near the plant lower limit (0.2).

Figure 9-5 shows pumping rate and depth to water table. The farm water table fluctuated around the water table control limit (1.5m deep), high pumping rates (especially 5mm/d maximum rate) only occurred during the periods of high water tables.

Figure 9-6 shows the recharge in the farm and soil water content. Large recharge events contributed significantly to the amount of water recharging to the water table. The total annual recharge varied from 40-260mm. There were numerous recharge events less than 10 mm/d. However, often a significant proportion of the total annual recharge occurred in a few large events of 20-50 mm/d.

Figure 9-7 and Figure 9-8 show that upflow in the farm follows evapotranspiration. The upflow rate is normally below 0.5 mm/day and U/ET_C is less than 0.1. Periods of high upflow were associated with shallow water tables.

Figure 9-9 shows that shallow water tables in the basin soil are related to high water levels in the basin. The basin often dried up in summer. When the basin had water, the soil below the basin was saturated and at times unsaturated.

Figure 9-10 shows the division of total evaporation in the basin system, between open water evaporation when the basin has water and soil evaporation when the basin is dry. Figure 9-11 shows the ratio of basin evaporation to open water evaporation. These figures show that the basin was frequently dry. This usually occurred in summer, but sometimes even in winter.

Figure 9-12 and Figure 9-13 show that the basin soil may become quite dry in summer when the basin was dry. Whereas when the basin was ponded, the soil water content was generally quite stable around the drained upper limit. This is controlled by the leakage rate through the basin bottom which is fixed at the saturated hydraulic conductivity.

Figure 9-14 shows that basin recharge occurs when the basin is ponded and the soil water content is above the drained upper limit (0.35 in this example). The recharge rate is controlled by the soil water content regime, which itself is a function of the leakage rate. Because the leakage rate is a fixed value described above, the resulting recharge rate is generally quite stable. However, large recharge events can occur when the basin soil is saturated.

Figure 9-15 shows that basin upflow is normally below 0.5mm/day and U_B/E_{BS} is less than 0.1. Upflow from the basin soil was relatively infrequent, coinciding with periods when the basin was dry.

Figure 9-16 shows that interchange between the farm and basin soil is proportional to the water table difference between them. The water table under the basin was normally about 0.6m higher than the water table in the farm. Only rarely was there a large difference between the farm and basin, thus the interchange was usually small, less than 1.5 mm/d. The interchange can be seen to closely follow the basin recharge pattern in Figure 9-14.

The above results are reasonable in terms of conforming to our understanding of soil water movement theory, crop soil water relations and soil physics generally. The values obtained are within reasonable bounds and compare well with the limited empirical evidence regarding such a farm and basin system.

To further examine the performance of the model, a simulation was conducted for comparison with field data from a farm and basin system in the MIA.

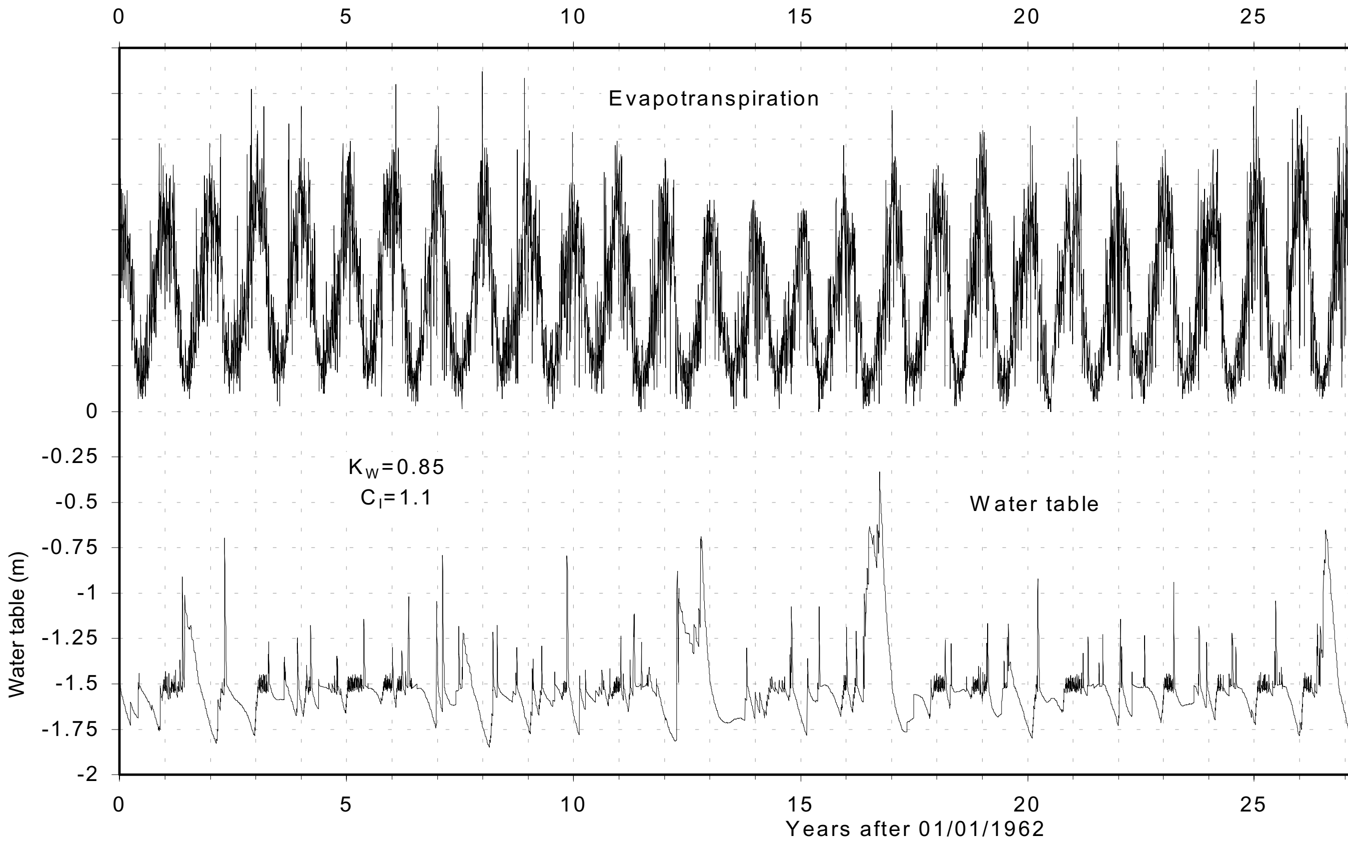


Figure 9-1. Evapotranspiration and water table depth in a citrus farm for a 7.5% basin area

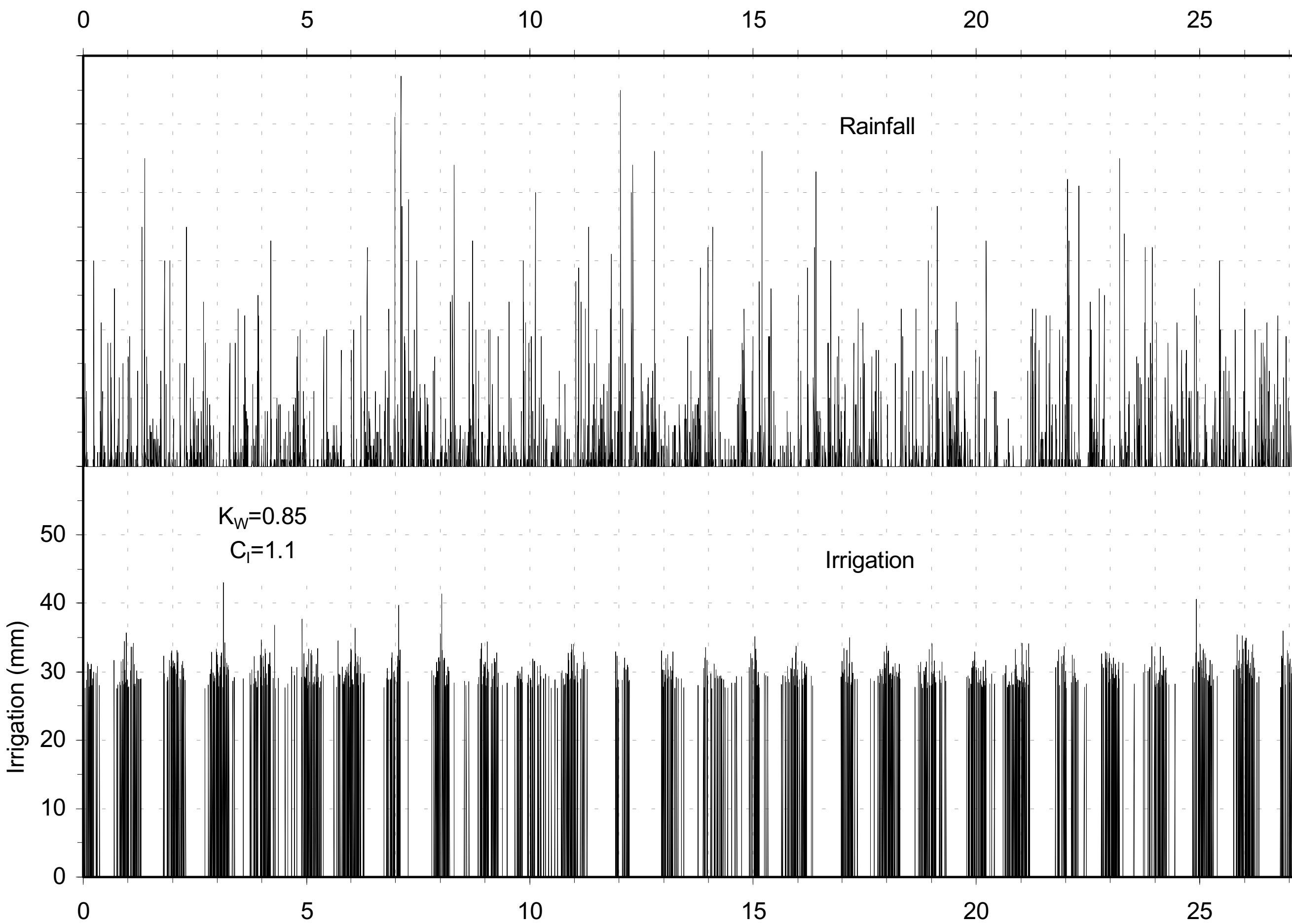


Figure 9-2. Rainfall and irrigation requirement for a 25mm maximum allowable water deficit

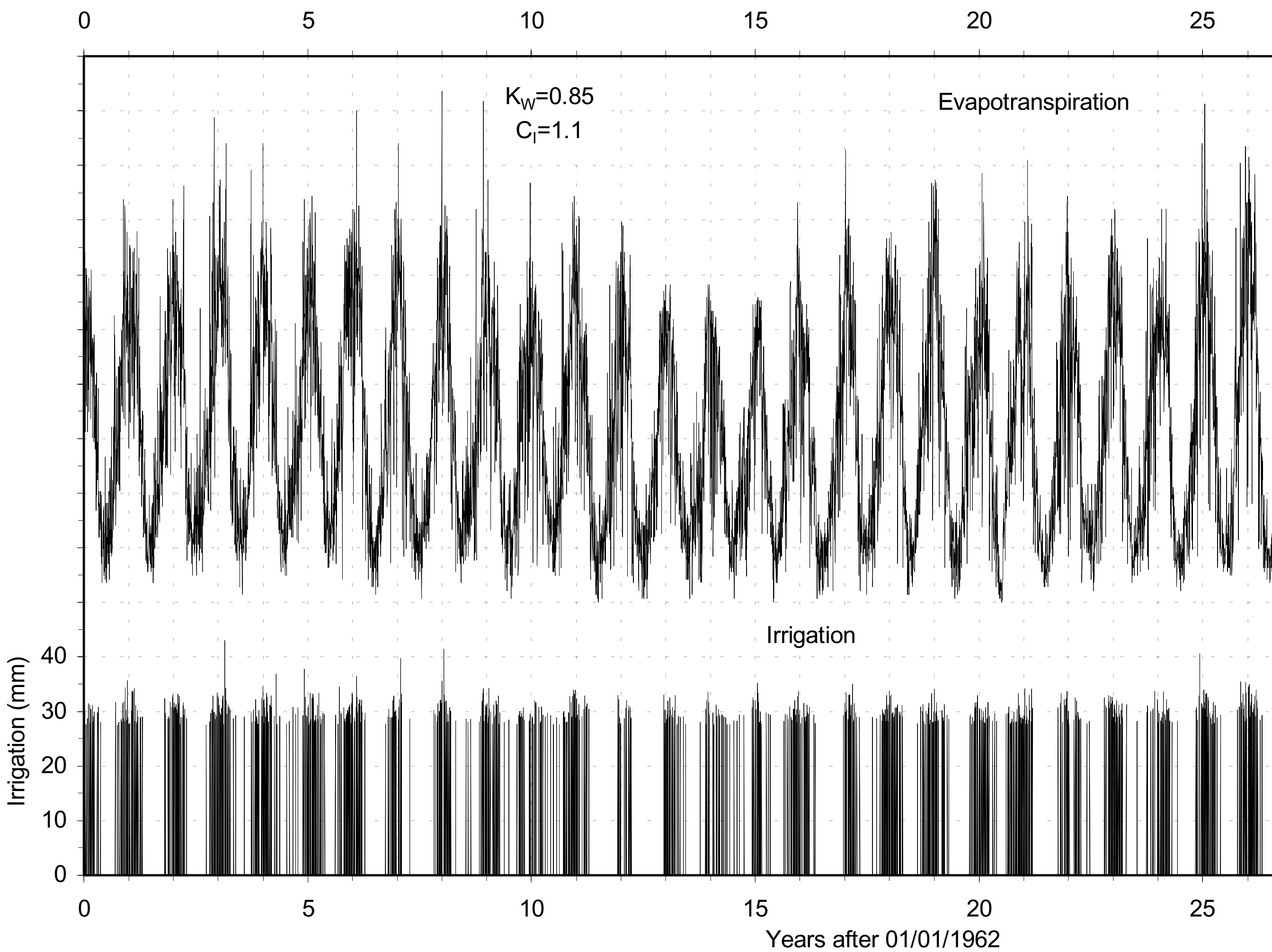


Figure 9-3. Evapotranspiration and irrigation requirement for a 25mm maximum allowable water deficit

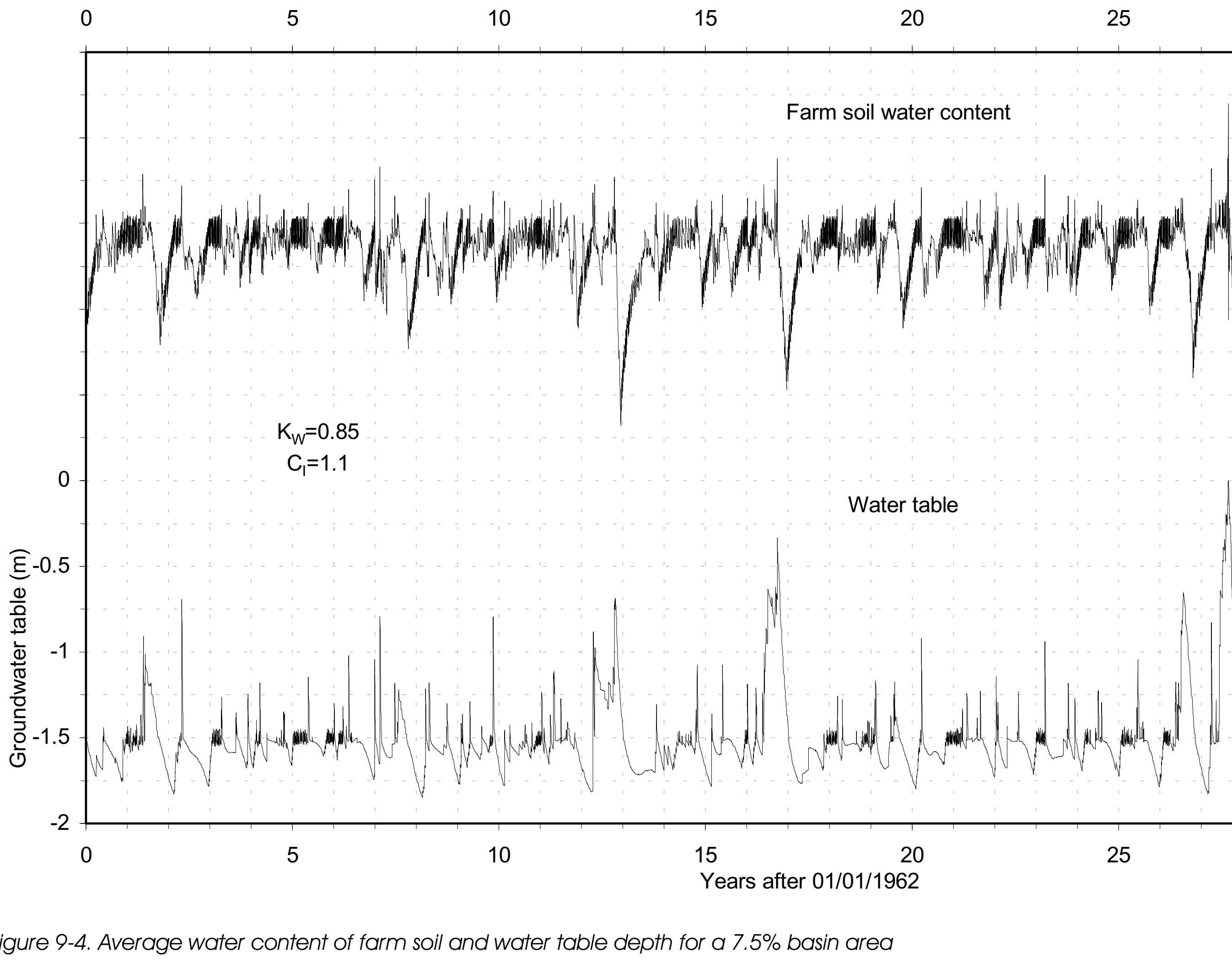


Figure 9-4. Average water content of farm soil and water table depth for a 7.5% basin area

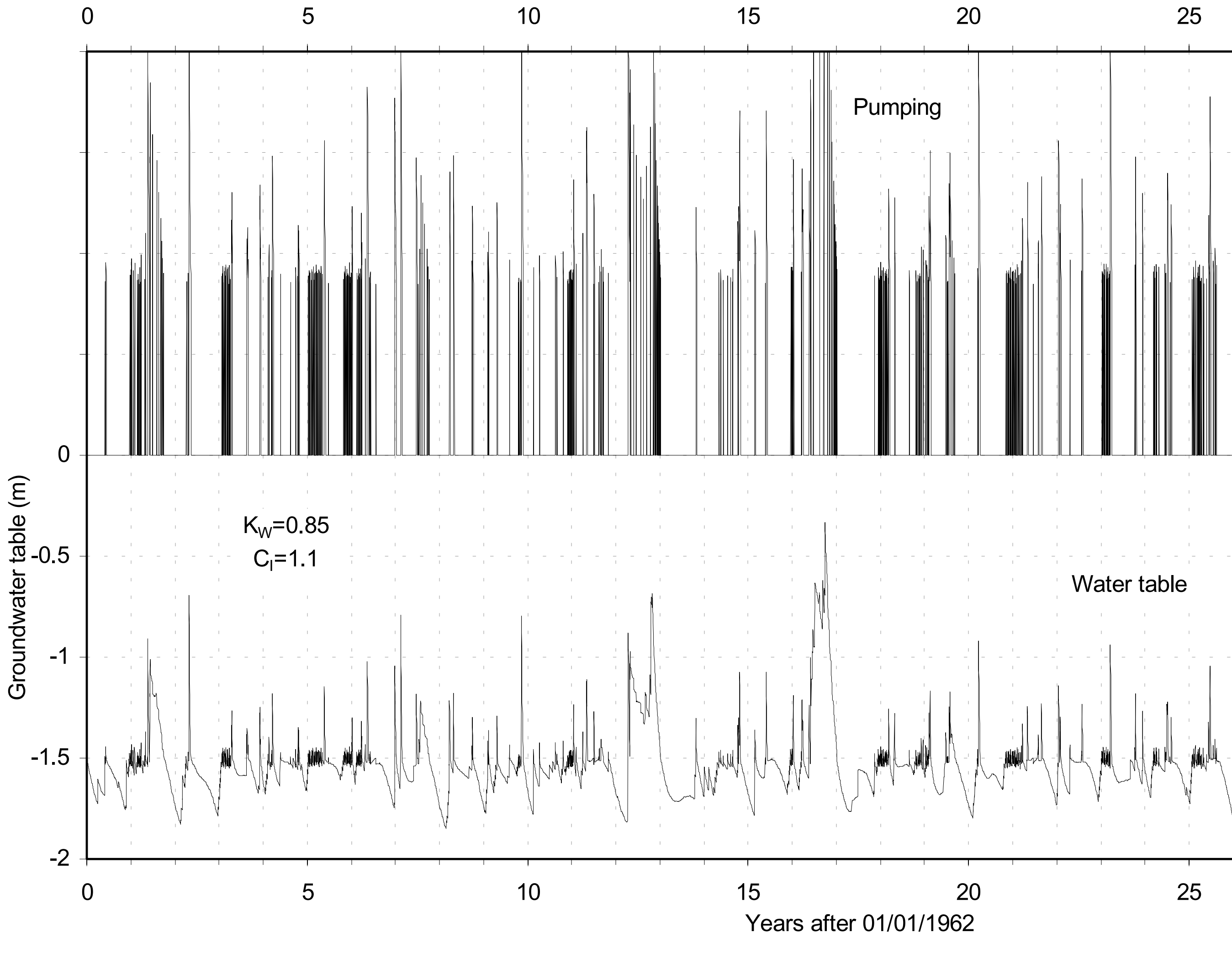


Figure 9-5. Farm subsurface drainage and water table depth for a 7.5% basin area

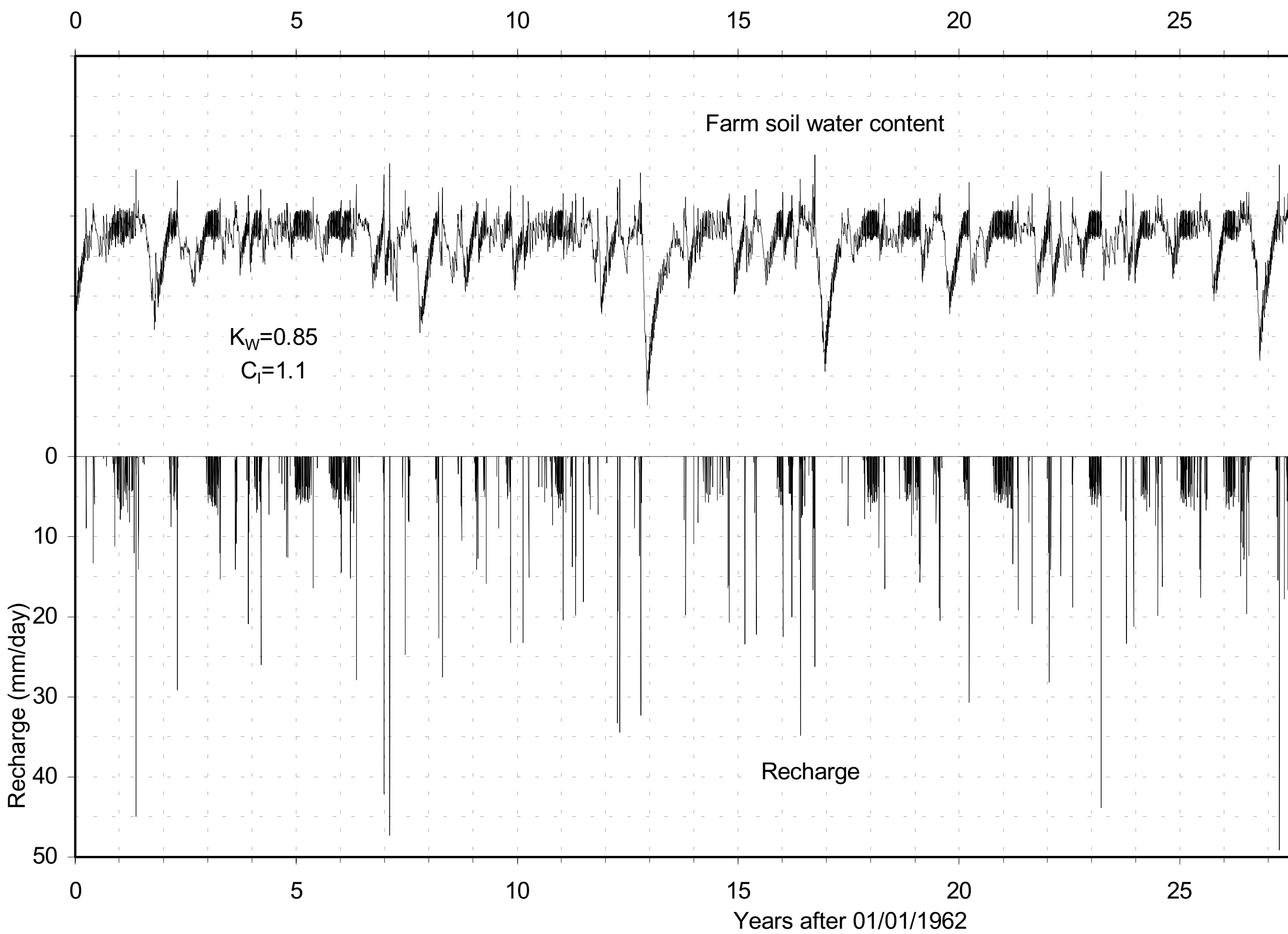


Figure 9-6. Recharge in the farm and average water content of the soil for a 7.5% basin area

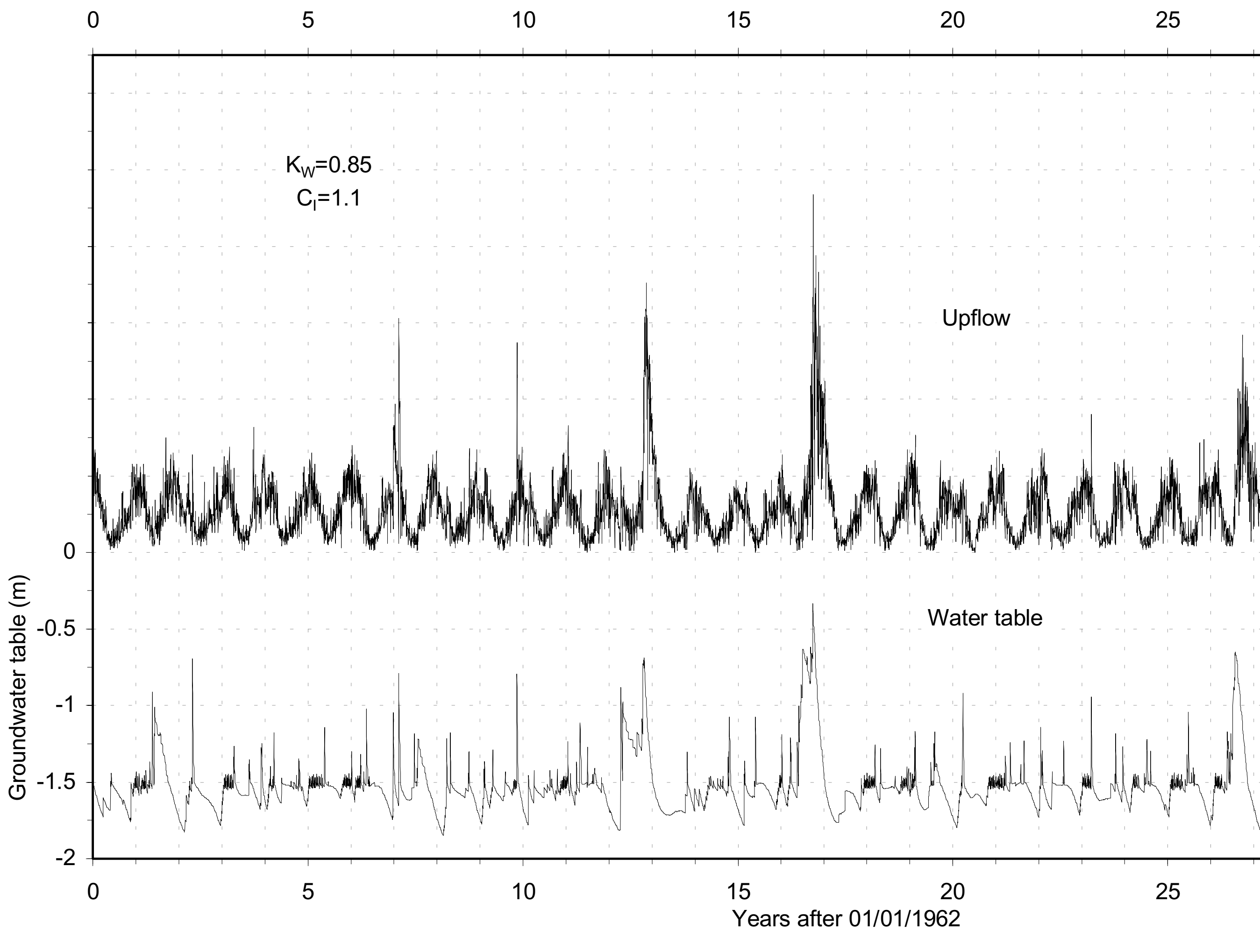


Figure 9-7. Farm upflow and water table depth for a 7.5% basin area

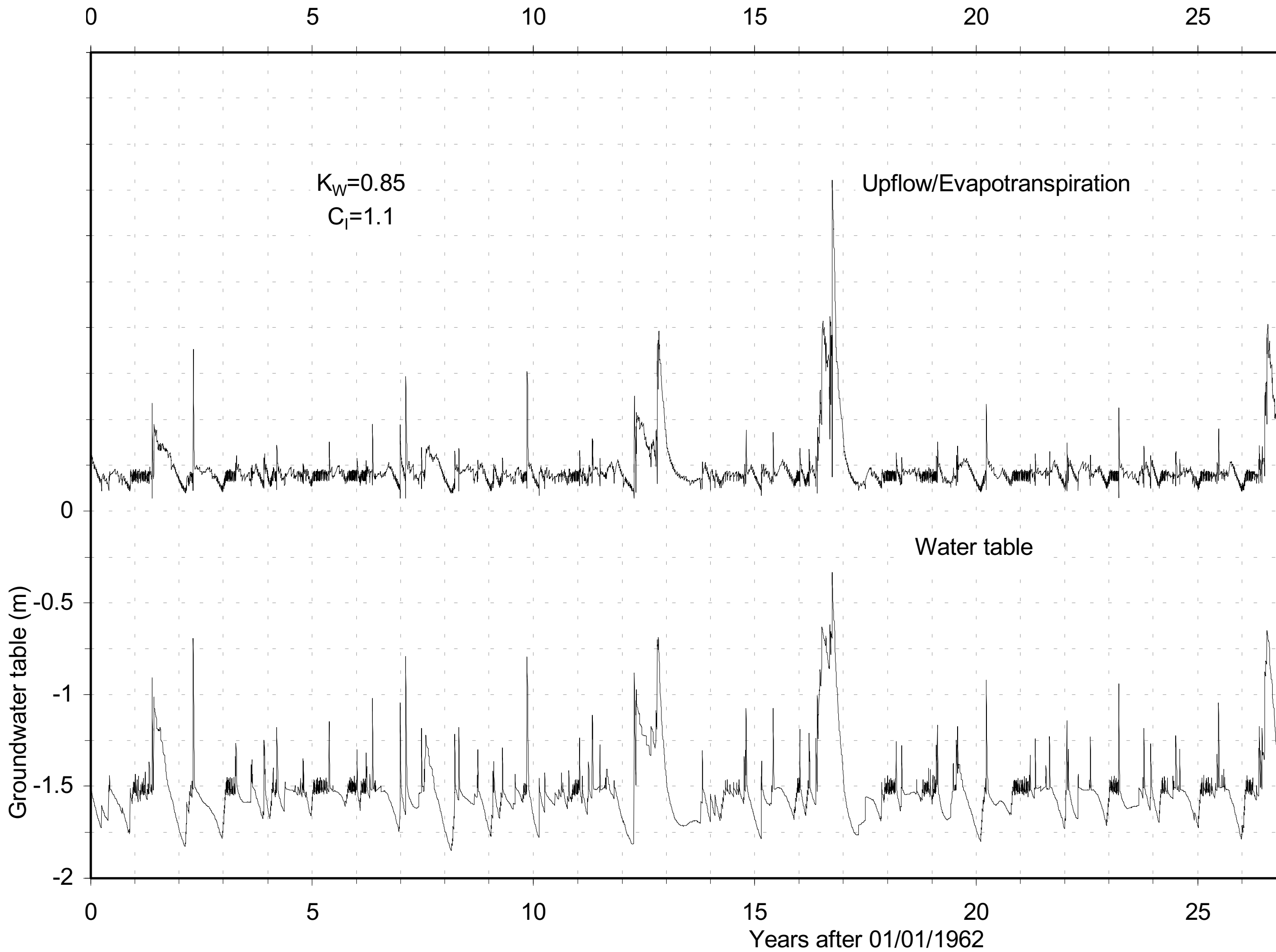


Figure 9-8. Ratio of upflow to evapotranspiration and water table depth for a 7.5% basin area

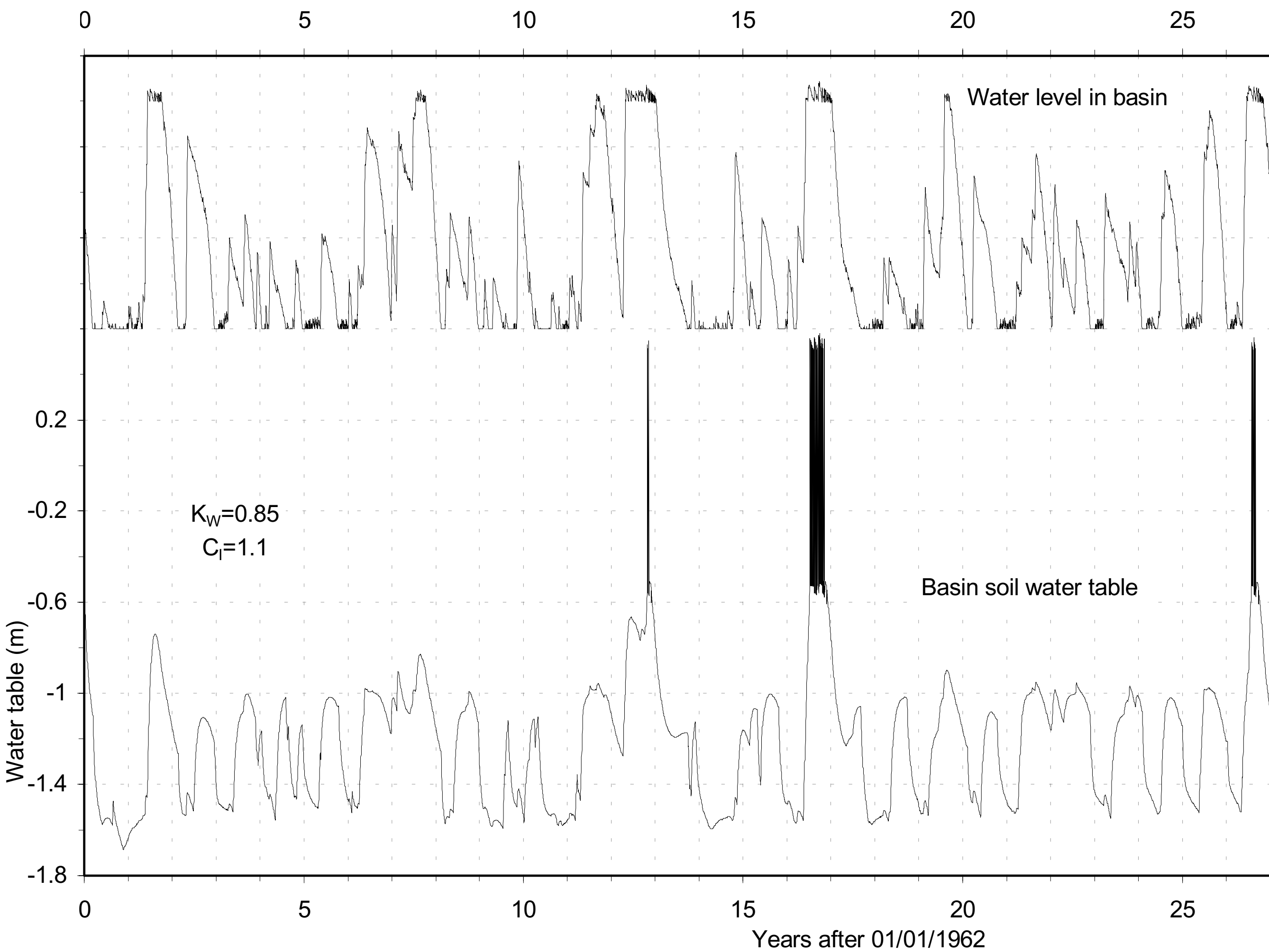


Figure 9-9. Basin water height and water table in the basin soil for a 7.5% basin area

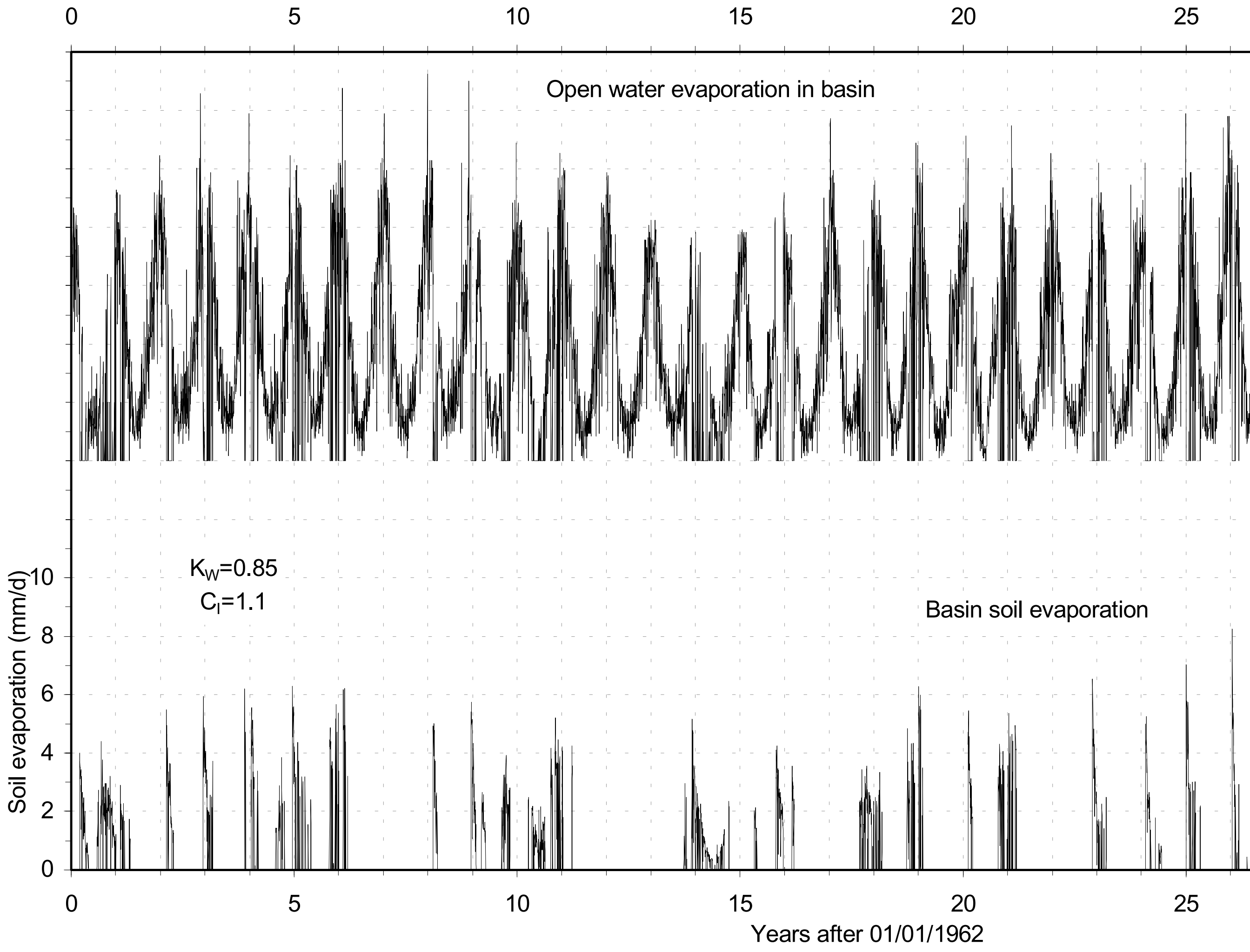


Figure 9-10. Open water evaporation from basin and basin soil evaporation for a 7.5% basin area

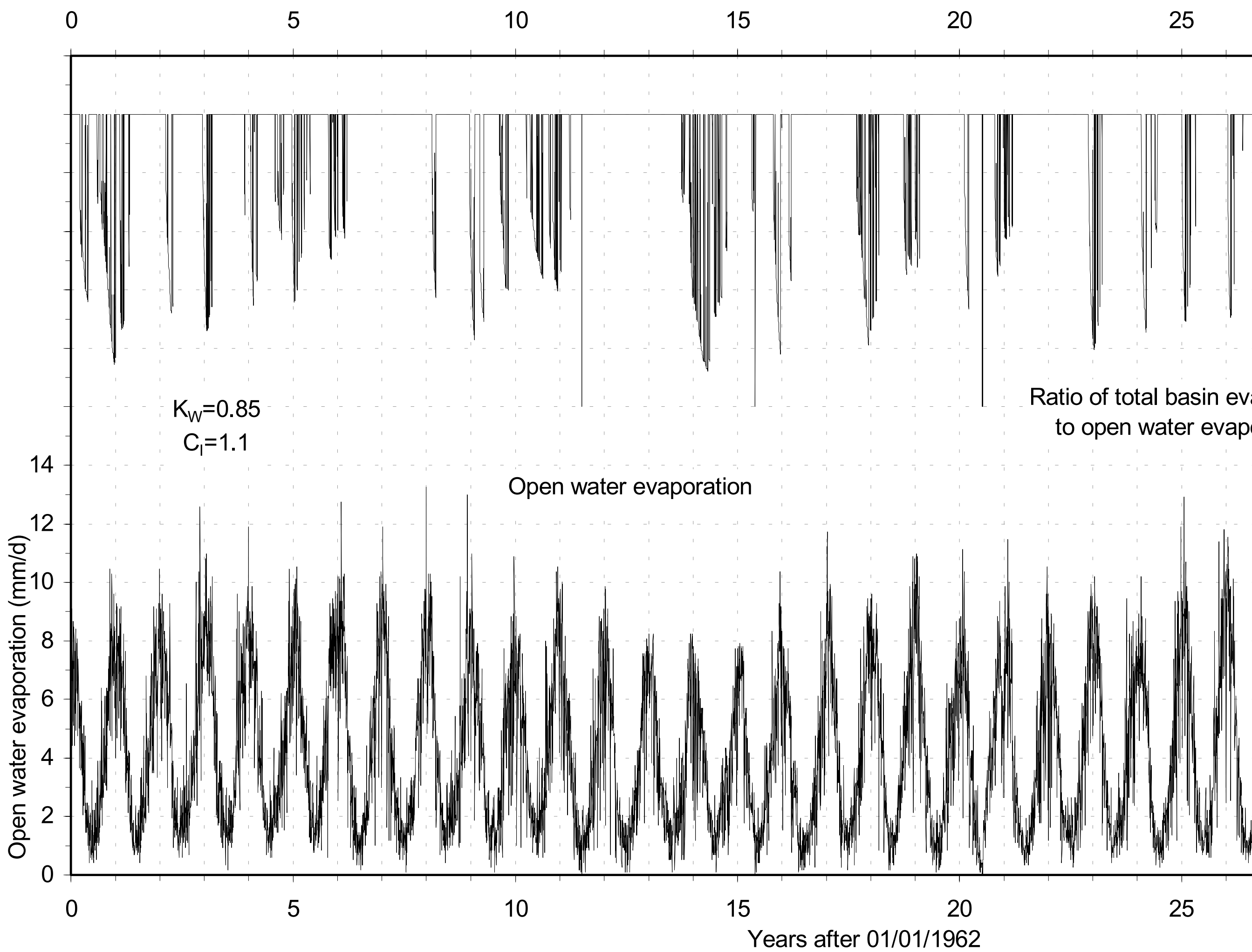


Figure 9-11. Open water evaporation rate and ratio of total basin evaporation to open water evaporation for a 7.5% basin are

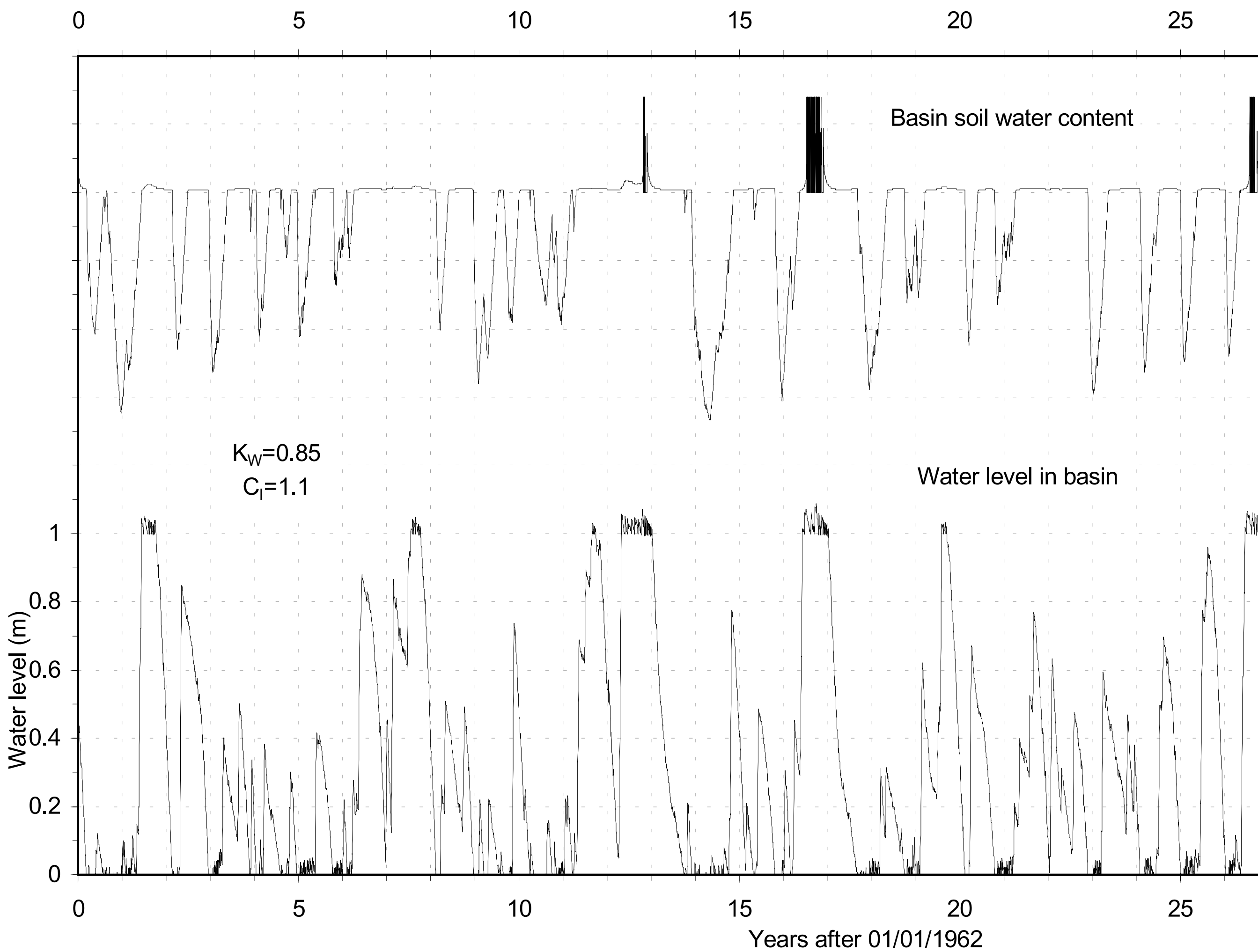


Figure 9-12. Average water content of basin soil and water level in basin for a 7.5% basin area

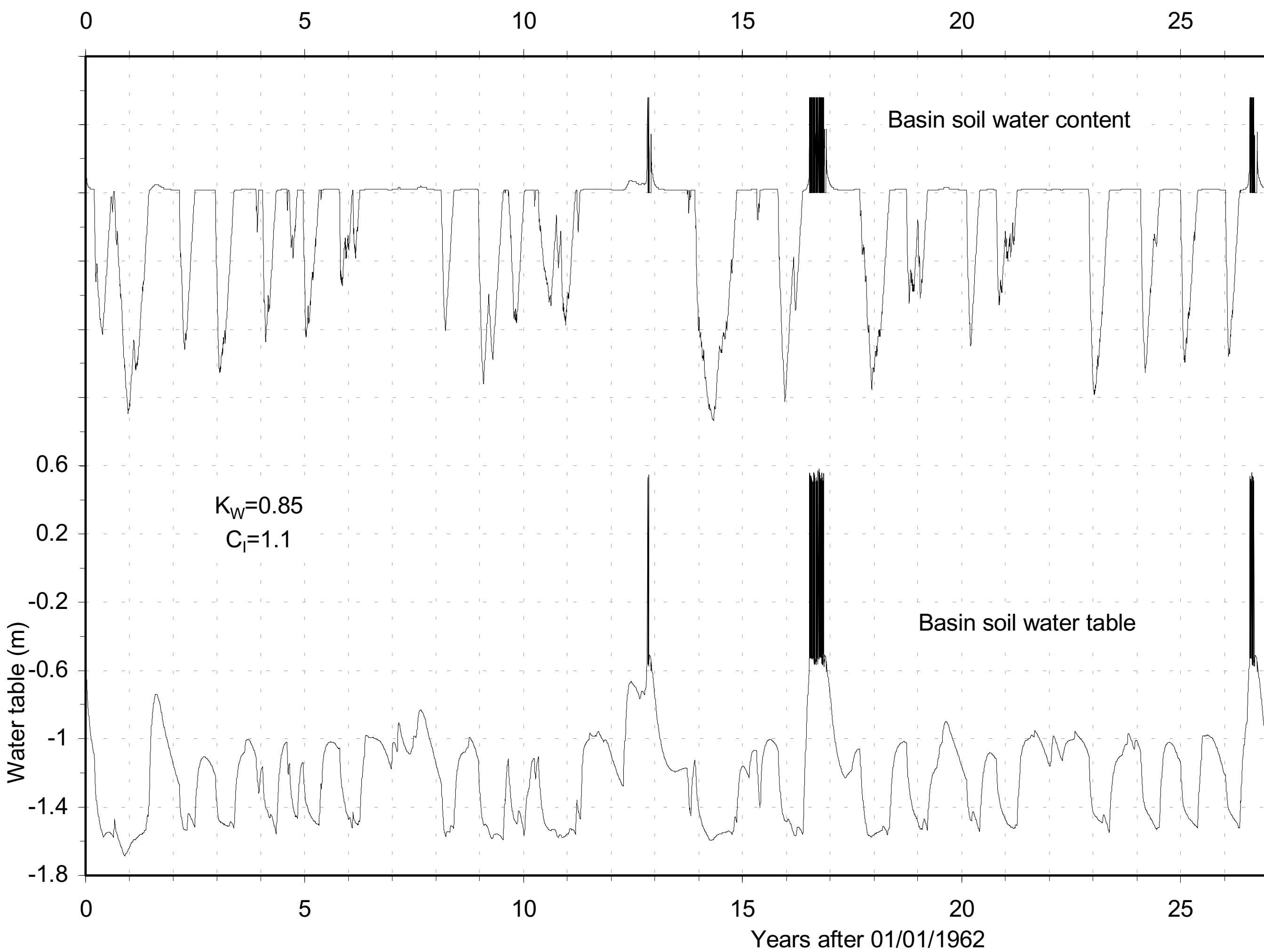


Figure 9-13. Basin soil average water content and water table for a 7.5% basin area

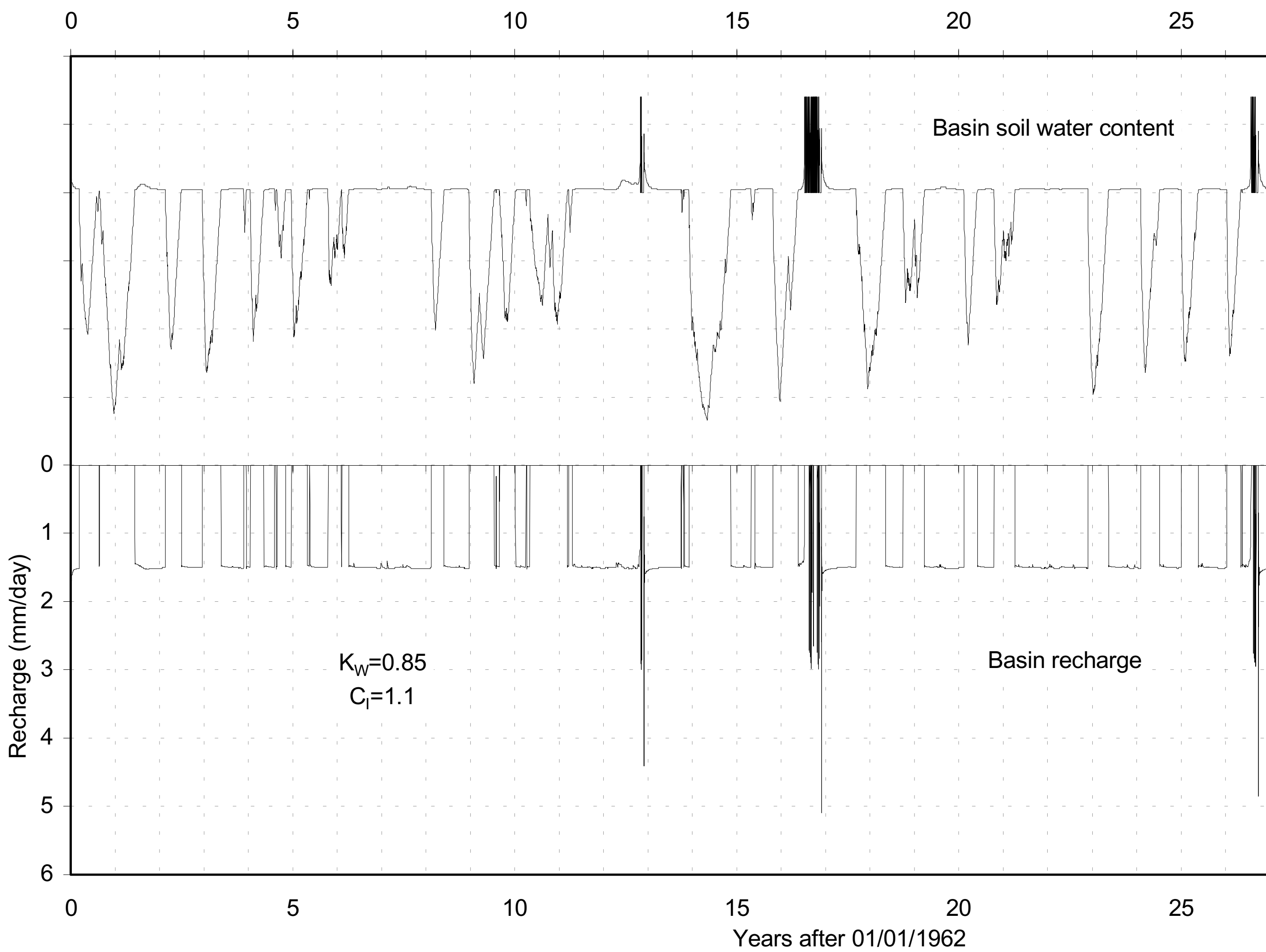


Figure 9-14. Basin recharge and average water content of the soil for a 7.5% basin area

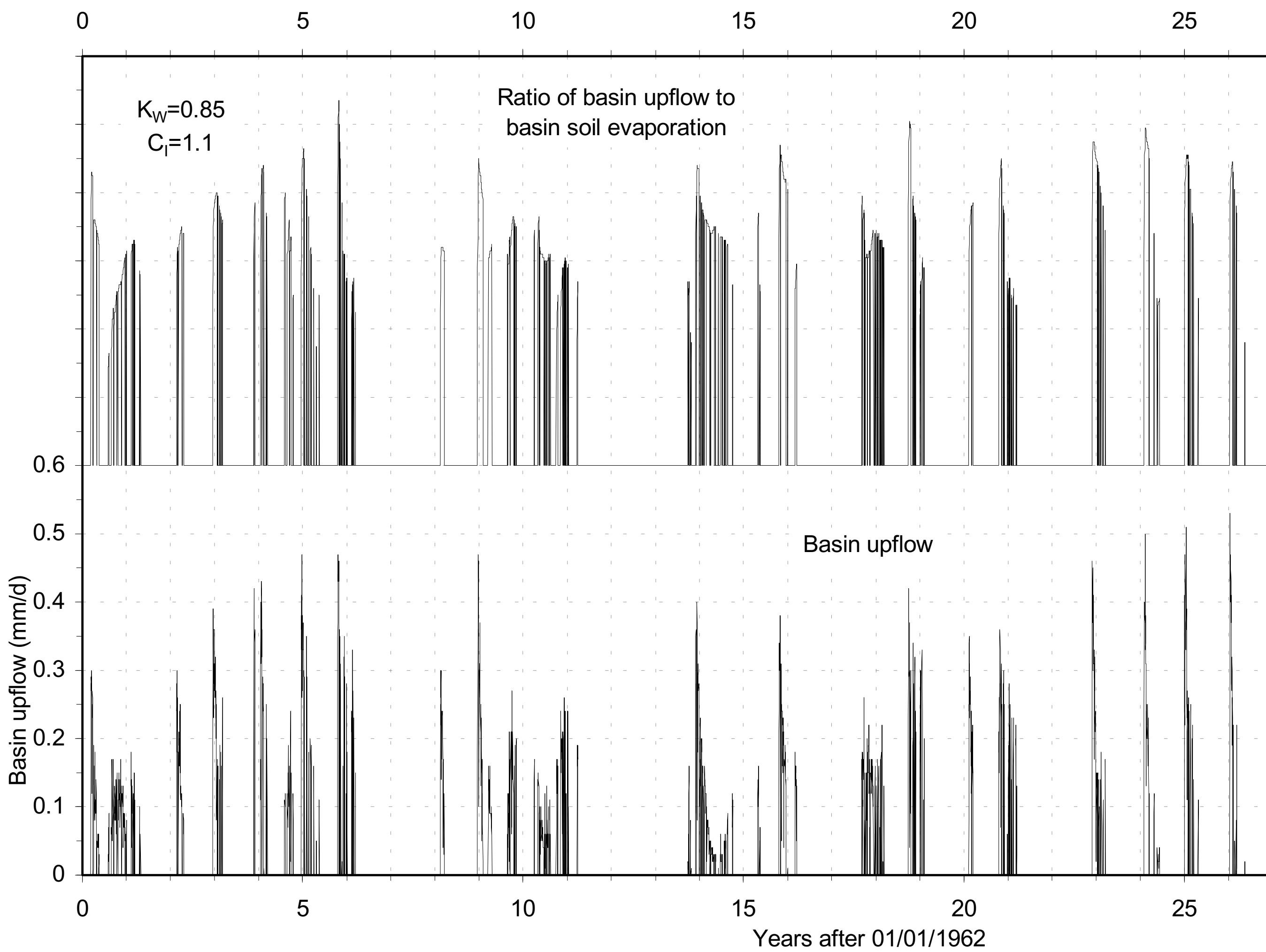


Figure 9-15. Basin upflow and ratio of basin upflow to basin soil evaporation for a 7.5% basin area

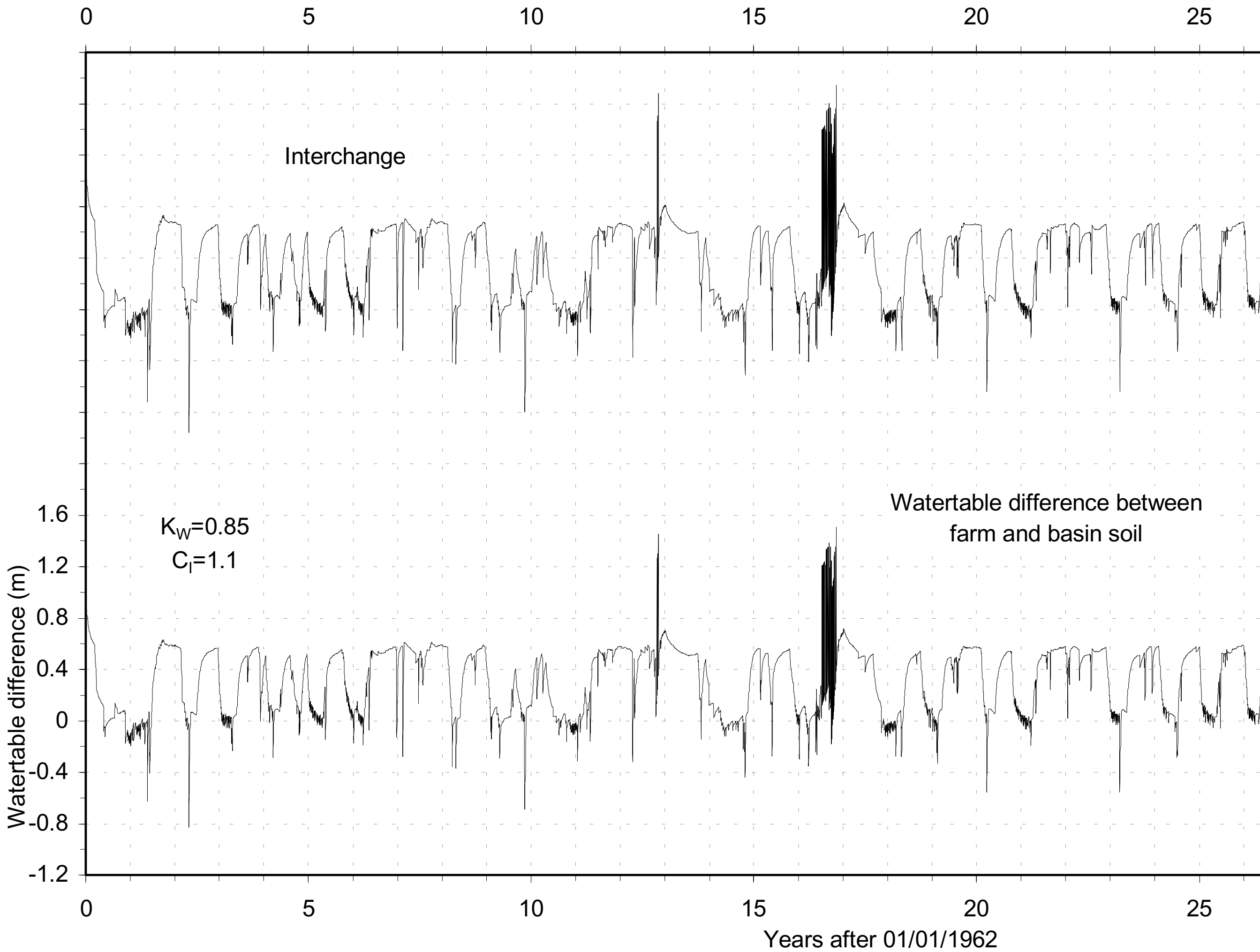


Figure 9-16. Water table difference between farm and basin soil (H_B– H_F) and corresponding interchange for a 7.5% basin area

9.3 Comparison with Field Data

The model was also tested against a data set obtained from an on-farm basin near Griffith in the MIA (Christen pers.comm.). The basin and farm were intensively monitored from soon after construction for a 17 month period. The basic information on the farm is as follows:

§ Crop - 1 and 2 year old grape vines;

§ Farm area drained (A_F) was 25 ha, for first 8 months (Feb. 97 – Sept. 97) and then 50ha for the remaining 9 month period (Oct. 97 – Jun. 98);

§ Total basin area (A_B) was 1.89 ha for the whole period;

§ Maximum allowable water depth in the basin (H_{RA}) was 750 mm;

§ For the first 8 months the farmer irrigation was by complete flooding of the inter row at an estimated 30 mm soil water deficit and resulting average irrigation efficiency (C_I) of about 1.29. In the following 9 month period the irrigation practice was changed with the assistance of the research team in order to reduce the drainage volume which had led to the evaporation basins becoming completely full after one season. The irrigation method was changed to small furrows near the vines and the deficit before irrigation changed to about 70 mm. This led to an average irrigation efficiency of about 1.025 ;

§ The subsurface pipe drains were spaced every 36.5 m and ranged from a minimum depth of 1.7 m to a maximum of 2.4 m deep. In the first 8 months the farmer allowed the pump to run continuously, this was estimated to result in an equivalent pumping control depth of 1.8 m, the average depth of drains in the farm. During the following 9 months the pumping control depth was set at 1.5 m;

§ The saturated hydraulic conductivity of the soil in the farm (K_{SF}) was estimated as 0.2 m/d from soil analysis and that at the basin bottom (K_{SB}) was estimated as 0.0035 m/d from water balance calculations;

§ The open water evaporation coefficient (K_W) was measured as about 1, i.e. equivalent to pan evaporation;

§ The simulation was started in February, which was about 6 weeks after pumping into the basin was started, at this stage the basin held 0.498 m of water and the farm water table was about 1.5 m deep.

The simulation results for this basin/farm system and the measured field data are listed in Table 9-3, Table 9-4 and. The model simulates the actual irrigation regime well, Figure 9-17, starting and ending the irrigation seasons at the right time and applying the correct amounts of water. By altering the irrigation deficit the model was adjusted to give a reasonable simulation of the irrigation interval and coupled with adjustment of the efficiency term satisfactorily modelled the total amount applied.

Since the water applied has been well represented by the model the resulting drainage is also very close to that measured both in magnitude and timing, Figure 9-18. However, towards the end of the simulation some drainage was measured that did not occur with the modelling. This may be due to localised recharge after irrigation such as water standing over drains in low sections of the farm and even leakage from on-farm irrigation channels.

The water level in the basin reflects the periods of drainage, Figure 9-19. The basin remains full or nearly full for the first 10 months then as the change in irrigation practices take effect and the drainage amounts decline the basin level drops rapidly. The basin dries out completely in month 14 according to the model, in reality the basin was dry about a month later. The model reflects the trend in basin level from full to empty, although in the first 12 months the model fills the basin and keeps it full more than was observed.

The result of the water balance simulation is a farm water table which is compared with actual observations in Figure 9-20. The observed value is a farm average from a number of piezometers spread across the farm. The modelled and measured values are actual daily values, not averaged over time. Thus in comparing the values it should be considered that the length of time since the last irrigation and the exact location of the piezometers with regard to the drainage system and the farm topography will have a significant effect.

During the first four months the model reflects the observed values until there is late irrigation in the first season. This raises the modelled water table which then declines steadily without, any further recharge, to the drain level of 1.8 m. The observed water tables then began to rise and due to small amounts of recharge after seven months. The water table then dropped away during the latter part of the irrigation season to well below the drain depth. That the water tables dropped below drain depth indicates that either there is leakage deeper in the system, not a closed boundary, or that capillary upflow continues from a greater depth than the model predicts.

Basin leakage was modelled, assuming saturated conditions below, using the ‘SIMPLE’ option controlled by the soil hydraulic conductivity, 4.3.1. This option did not reflect the high rate of leakage early but when the leakage stabilised the modelled and measured values are comparable,

Figure 9-21. During the period with stable leakage, months 3 – 13, the averages were 52 mm and 51 mm leakage per month by measurement and modelling respectively. For the last four months the measured leakage is given as zero, this is not quite the case as there was water pumped into the basin but not enough to cover the whole floor area. This made field estimates of leakage impossible. During this period the model predicted some small amounts of leakage which there would have been.

Overall the model compared well with the field data. The general trends observed in the field are reflected in the model. The model was able to follow these trends, including the changes due to the dramatic change in irrigation and drainage management in the second season. An important aspect of the model is that it was able to correctly simulate the irrigation regime, which is the major input of water to the system. With irrigation properly modelled the other aspects of the water balance are more likely to be correct. Overall this comparison gives us reasonable confidence in the model with regard to a combined farm and basin system. No other data sets of a drainage system with basin have been found to further test the complete model. To aid further testing the evaporation basin can be removed from the system and thereby the farm water balance tested alone, this is undertaken in the next section.

Table 9-3. Measured and modelled results of irrigation, drainage and crop water use

MONTHS starting Feb 97		IRRIGATION mm				DRAINAGE mm				
		Monthly		Cumulative		Monthly		Cumulative		
No.	**Month**	**Measured**	**Modelled**	**Measured**	**Modelled**	**Measured**	**Modelled**	**Measured**	**Modelled**	**Ca**
1	Feb	114	164	114	164	27	23	27	23	
2	Mar	140	85	254	249	21	17	48	40	
3	Apr	44	78	298	326	19	24	66	64	
4	May	68	0	366	326	7	13	73	77	
5	Jun	0	39	366	365	6	6	79	84	
6	Jul	0	0	366	365	9	6	89	90	
7	Aug	0	0	366	365	6	8	95	98	
8	Sep	0	0	366	365	9	9	103	107	
9	Oct	0	72	366	437	5	9	108	116	
10	Nov	162	73	528	510	17	8	124	124	
11	Dec	139	148	667	658	7	0	131	124	
12	Jan	82	74	749	731	6	0	137	124	
13	Feb	130	144	879	875	0	0	138	124	
14	Mar	60	75	939	950	0	0	138	124	
15	Apr	83	73	1022	1023	2	0	139	124	
16	May	0	0	1022	1023	1	0	140	124	
17	Jun	0	0	1022	1023	0	0	140	124	
	SUM	**1022**	**1023**			**140**	**124**			

Table 9-4. Measured and modelled basin water level

MONTHS		BASIN WATER LEVEL mm			
Starting Feb 97		Monthly		Cumulative	
No.	Month	Measured	Modelled	Measured	Modelled
1	Jan	498	498	498	498
2	Feb	616	506	1114	1004
3	Mar	606	534	1720	1538
4	Apr	532	681	2251	2219
5	May	636	749	2887	2968
6	Jun	635	756	3522	3724
7	Jul	616	747	4138	4471
8	Aug	611	756	4748	5227
9	Sep	746	751	5494	5978
10	Oct	560	771	6053	6749
11	Nov	545	714	6598	7463
12	Dec	355	401	6953	7864
13	Jan	318	173	7271	8037
14	Feb	90	0	7361	8037
15	Mar	0	0	7361	8037
16	Apr	0	0	7361	8037
17	May	0	0	7361	8037
18	Jun	0	0	7361	8037

Table 9-5. Measured and modelled fa

DATE	FARM	
	Monthly	
	Measured	Mode
02-Feb-97	-1.5	-1
28-Feb-97		-1
30-Mar-97	-1.8	-1
30-Apr-97		-1
30-May-97	-1.9	-1
18-Jun-97	-2.0	-1
10-Jul-97	-2.0	-1
14-Aug-97	-1.9	-1
25-Sep-97	-1.6	-1
30-Oct-97	-1.5	-1
28-Nov-97	-1.6	-1
15-Dec-97	-1.5	-1
07-Jan-98	-1.9	-1
29-Jan-98	-2.0	-1
26-Feb-98	-2.5	-1
23-Mar-98	-2.3	-1

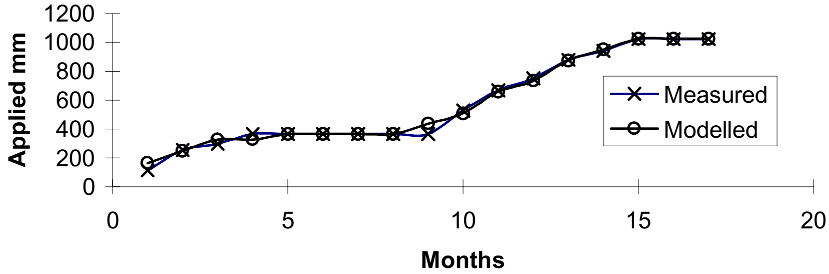


Figure 9-17 Cumulative measured and modelled irrigation

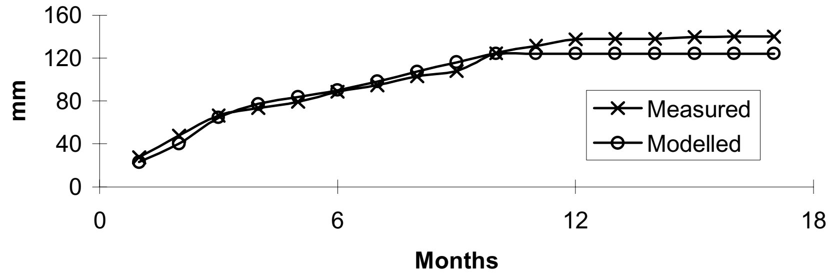


Figure 9-18. Cumulative measured and modelled subsurface drainage

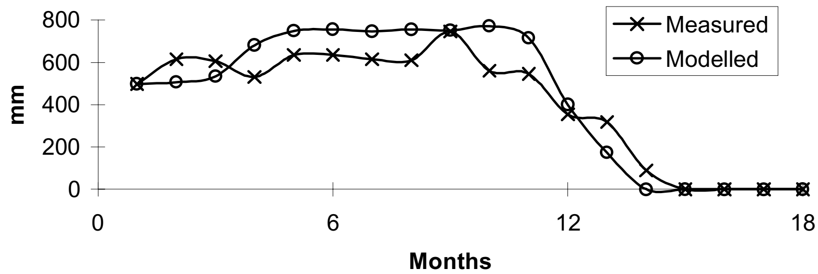


Figure 9-19 Measured and modelled water level in basin

Figure 9-20 Measured and modelled water table in farm

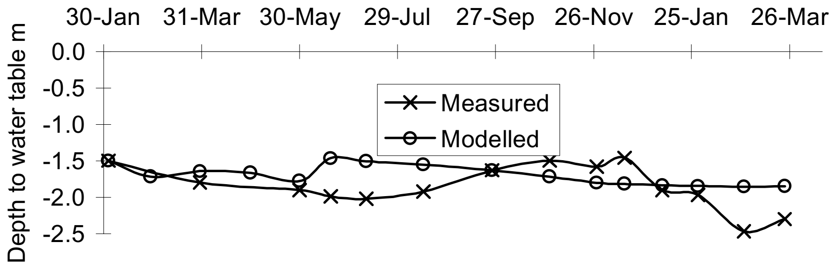
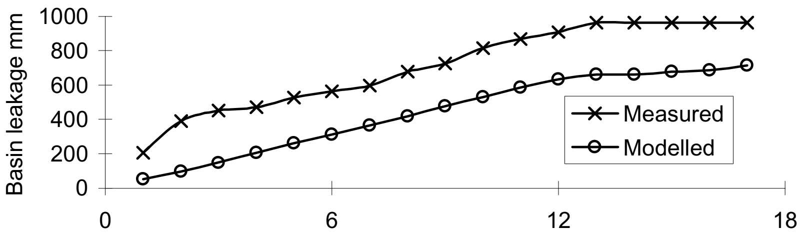


Table 9-6 Measured and modelled basin leakage

MONTHS starting Feb 97		BASIN LEAKAGE mm			
		Monthly		Cumulative	
No.	Month	Measured	Modelled	Measured	Modelled
1	Jan	205	51	205	51
2	Feb	185	46	390	97
3	Apr	62	52	452	149
4	May	19	56	471	205
5	Jun	56	56	527	261
6	Jul	38	51	565	312
7	Aug	31	53	596	365
8	Sep	82	55	678	420
9	Oct	48	57	726	477
10	Nov	91	53	817	530
11	Dec	53	56	870	586
12	Jan	39	47	909	633
13	Feb	55	28	964	661
14	Mar	0	0	964	661
15	Apr	0	17	964	678
16	May	0	8	964	686
17	Jun	0	29	964	715

Figure 9-21. Cumulative measured and modelled basin leakage



9.4 Comparison with SWAGMAN Destiny Model

The Basinman model was also tested against a soil crop water relations model SWAGMAN Destiny (1996) in order to assess the functioning of the Basinman model against a more sophisticated and previously tested model. As the Destiny model has no facilities for the inclusion of evaporation basins this comparison was used to assess the performance of the farm water balance in the Basinman model. For this simulation the Basinman model was run using the 'NOBASIN' option, thus there is no constraint to the subsurface drainage.

The simulations were for one year, starting on 1st July, using Griffith weather data, the crop was perennial pasture to simplify the use of crop factors in the Basinman model and also to have a crop that would require a lot of irrigation. The models were run assuming a Hanwood loam soil.

The same soil physical characteristics were used as far as possible, although the Destiny description of the profile is multilayered and thus much more detailed. The Basinman model assumes a homogeneous profile using average soil characteristics for the top 1.5 m.

The models had the same drain depth of 1.5 m, the Destiny model did not require a drain spacing as it is a point model that simulates tile drainage by emptying the layer in which the drains are allocated. In order to reflect the Destiny tile drainage characteristic of rapidly removing water from the profile the tile drains in the Basinman model were closely spaced (20 m) with a high capacity (50 mm/d). For the comparison the same irrigation deficit (50 mm), irrigation efficiency (1.2), water table depth (1.5 m) and soil moisture were used.

The outputs from the Destiny and Basinman simulations are summarised in Table 9-1

The potential ET was 58 mm lower with the Basinman simulation although the crop ET was 37 mm higher. Thus the water demand for both simulations was practically identical, however the irrigation applied was significantly lower with the Basinman model, 1408 mm compared to

1668 mm. The amount applied per irrigation was the same for both models but the Destiny model had four extra irrigations, Figure 9-22. This was due to the Basinman model delaying irrigation if on the day irrigation was due there was any rain. This resulted in a more efficient use of rainfall with the Basinman model.

Consequent to the extra irrigation application with the Destiny model there was 193 mm more tile drainage, Figure 9-23 .The Destiny tile drainage occurs over short discrete periods with no drainage in the interval. This is different from the Basinman drainage that occurs over the whole period. This reflects the true relationship between water table height and drainage rate which is not simulated in the Destiny model. The resulting water table is shown in Figure 9-24. Before irrigation starts (day 72), there are two rainfall events which cause the Basinman water table to rise which does not occur in Destiny. Once the irrigation season starts the water table regimes for both models are similar with many small fluctuations reflecting the irrigation pattern. The Destiny water table however falls quickly back to the drain level whereas the Basinman water tables have a much longer recession curve. This is due to the Destiny method of emptying a soil layer compared to a head dependant flow in Basinman. After irrigations have finished (day 287 and 296) there are water table fluctuations caused by rainfall, the Basinman model has much greater rises due to these rainfall events with much slower recession. Overall the average daily water table height from Basinman is 0.11 m higher than Destiny. This is a relatively small difference and the overall trends from both simulations are similar.

The results of the simulations from the two models are comparable in most aspects. The method of determining crop water use is similar in both models thus the resulting crop water demand is almost the same. The irrigation method has one slight difference in that Basinman has a rain delay that enables better use of rainfall. This resulted in Basinman applying 260 mm less irrigation water that Destiny. However, the irrigation intervals and amounts applied were almost the same. Due to the extra irrigation Destiny had more drainage water. This could have been expected to result in higher water tables with the Destiny model, however the converse was true. This was mainly due to the method of drainage applied in Destiny that allows very rapid drainage, not accounting for hydraulic resistance in water flow to a drainage system. However, the overall water table regime was similar for the two models.

Table 9-7. Comparison of simulation results from Destiny and Basinman

Variable	Destiny	Basinman	Difference
Total potential ET mm	1912	1854	-58
Total ETc mm	1521	1558	37
Total irrigation mm	1668	1408	-260
Irrigation / Etc	1.10	0.90	
Rainfall mm	468	467	
Crop water use ratio	0.71	0.83	
Irrigation & rainfall excess mm	615	317	-298
No of irrigations	26	22	
Av. irrigation, target 60mm	64	64	
Irrigation efficiency (target 1.2)	1.3	1.3	
First irrigation day	73	72	
Last irrigation day	287	296	
Tile drainage mm	540	347	-193
Tile drainage excess/deficit mm	-75	30	
Change in soil storage mm	10	-31	
Water balance error (totals)	65	-1	
Av. water table depth m	-1.48	-1.37	

Figure 9-22. Cumulative irrigation in Destiny Basinman comparison.

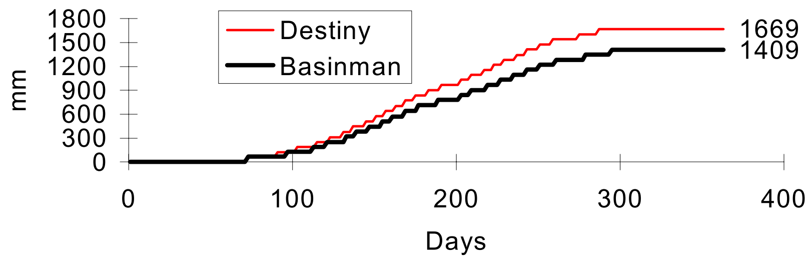


Figure 9-23. Cumulative tile drainage in Destiny Basinman comparison

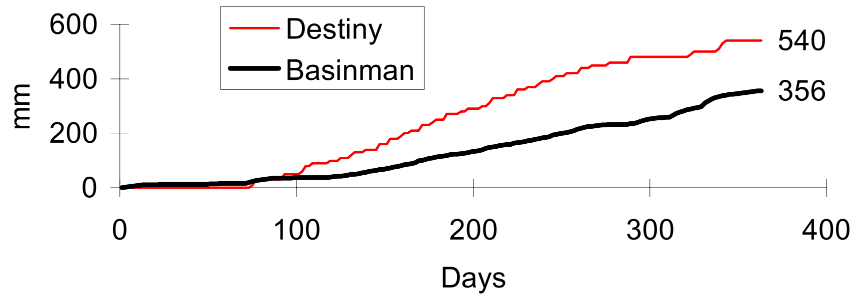
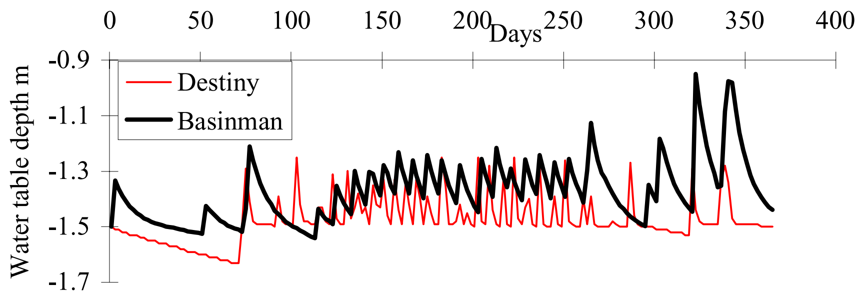


Figure 9-24. Water table from Destiny and Basinman simulations.



9.5 Using the Model to Determine a Suitable Basin Area

This model has been specifically developed to analyse the effects of an evaporation basin on the farm water balance. Using the 'OPTIMISATION' option in the model a number of basin area to farm area combinations can be analysed in order to determine the most suitable basin area. To determine the most suitable basin area there must be analysis of the farm water table to ensure that there is not excessive waterlogging and also analysis of the water regime in the basin itself to ensure the basin is not too small or too large. Thus the farm water table and basin water height are important outputs of the model critical to determining a suitable basin size.

Figure 9-25, Figure 9-26 and Figure 9-27 show the water table fluctuation in the farm and depth of water in the evaporation basin for basin areas of 5%, 7.5% and 10% respectively. Parameters used were the same as those in the previous physical process simulation, section 9.2. It can be seen that for a 5% basin area, the basin is rarely dry, almost always being completely full and thus restricting pumping. The water table in the farm is not well controlled and on many occasions it reaches the soil surface.

When the basin area is increased to 7.5%, obvious improvements are seen in both the farm and basin. The time when the basin is completely full is significantly decreased. The farm water table is better controlled and mainly fluctuates around 1.5m deep. However the time when the basin is dry is increased.

When the basin area is increased to 10%, only small improvements are seen in the farm water table and basin water depth. This means for basin areas greater than 7.5%, increasing basin area is less efficient and thus likely to be less economically attractive, under these simulation conditions.

To further quantitative understanding of the relationships between basin area and waterlogging control, the number of days the water table in the farm is above a given height is computed and expressed as a ratio of the total time. The same is done for depth of water in the basin. Figure 9-28 shows this function for water table depths of 0.4 to 1.5 m in the farm with different basin area to drained area ratios. These are averages of the 35 year simulation; Figure 9-29 is for water heights of 0 to 1m in the basin.

Considering the water table depth (H_{FA}) to control pumping (1.5 m in Figure 9-28), the corresponding line shows the maximum extent to which the water table can be controlled. This line may be called the water table control curve. In regard to the waterlogging depth (H_{WL}), the corresponding line shows the percentage of time when waterlogging occurs. This line may be called the waterlogging control curve. A one metre water table depth is used in this report for the assessment of waterlogging. The lowest water depth line (0 m) for the basin, corresponds to the fraction of time when basin contains water. This line may be called the basin ponded curve to represent the proportion of time the basin is dry. To analyse water discharge from the basin, the basin ponded curve shows the time when the basin evaporates water at the maximum rate (E_W). If we consider the allowable depth of water in the basin (1m in Figure 9-29), the corresponding line shows the percentage of time when basin is full, thus preventing pumping. This line may be called the basin full curve. This curve also shows the risk of overflow from the basin. Table 9-8 lists some critical values from Figure 9-28 and Figure 9-29.

Table 9-8. Fraction of time when some important conditions occur

	In the farm		In the basin	
Ratio of basin area (%)	Water table not controlled (<1.5m)	Waterlogging (<1m)	Basin ponded (>0)	Basin is full (>1m)
5	0.70	0.38	0.98	0.65
7.5	0.18	0.03	0.84	0.09
10	0.13	0.01	0.68	0.04

From Figure 9-28, Figure 9-29 and Table 9-8, it can be seen that when increasing the ratio of basin area from initially low values such as from 5% to 7.5%, then the rate of decrease in waterlogging is greatest. Whereas increasing the ratio of basin area at high values, such as from 7.5% to 10%, only creates small changes. The same tendency is found with the water table control curve and the basin full curve. These relationships allow for qualitative assessment of the improvements to both water table in the farm and basin water depth that occur from changing basin areas.

There is a different type of relationship for the basin ponded curve, which is flat before a threshold value (6.5% in Figure 9-29) and declines quite steeply after this value. This also indicates that too high a basin ratio would be suboptimal due to low utilisation of the basins' potential to evaporate water.

It has been shown that a reasonable selection of basin ratio is vital in terms of hydrological effectiveness and economical feasibility. From Figure 9-28, Figure 9-29 and Table 9-8, about a 7.5% basin ratio is likely to be near optimal for this situation. This ratio controls the water table depth below the desired depth (1.5m) for more than 80% of the time, prevents waterlogging for more than 90% of the time, keeps the basin ponded for more than 80% of the time, and only has the basin completely full 10% of the time.

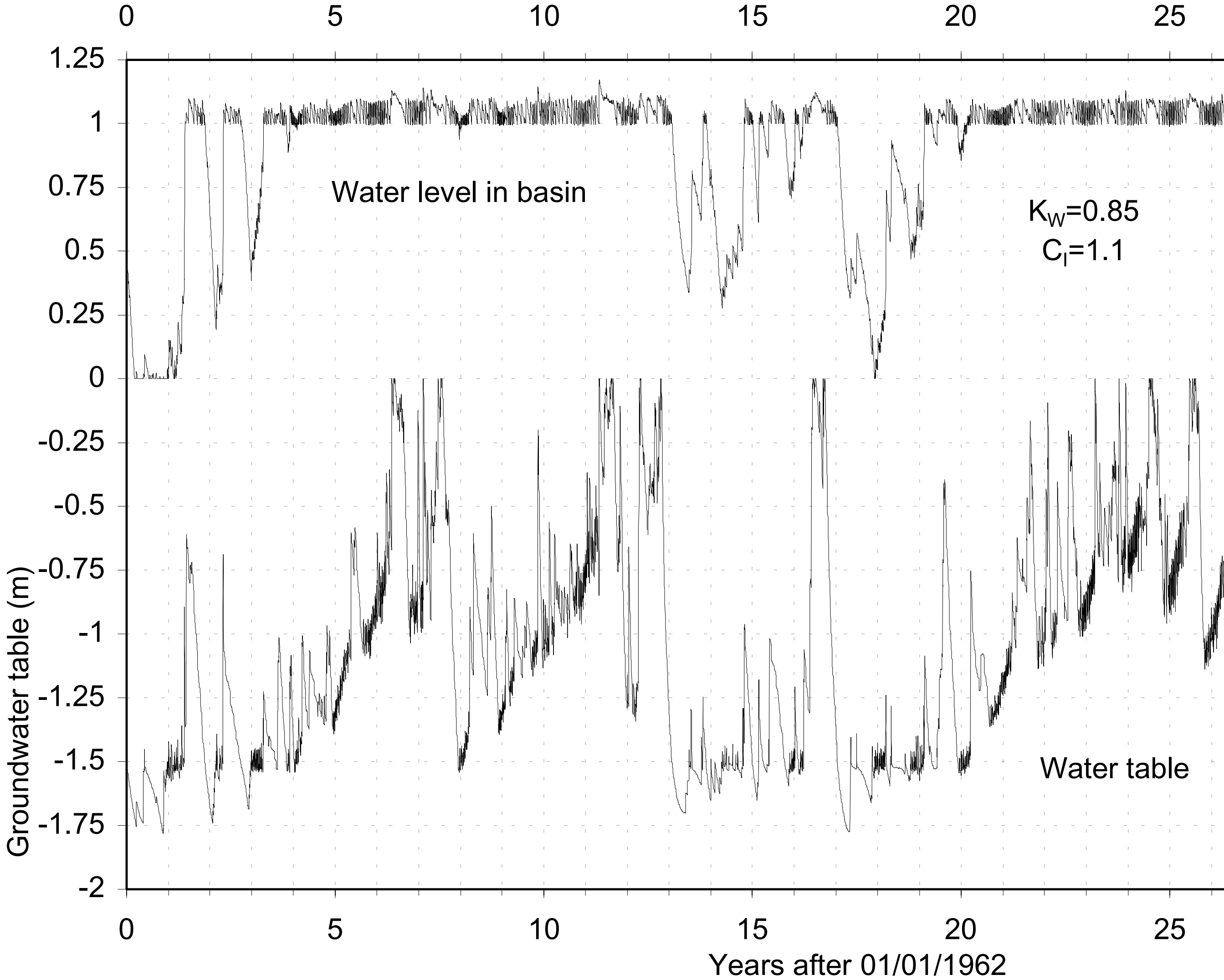


Figure 9-25. Water table depth in farm and basin water height for a 5% basin area

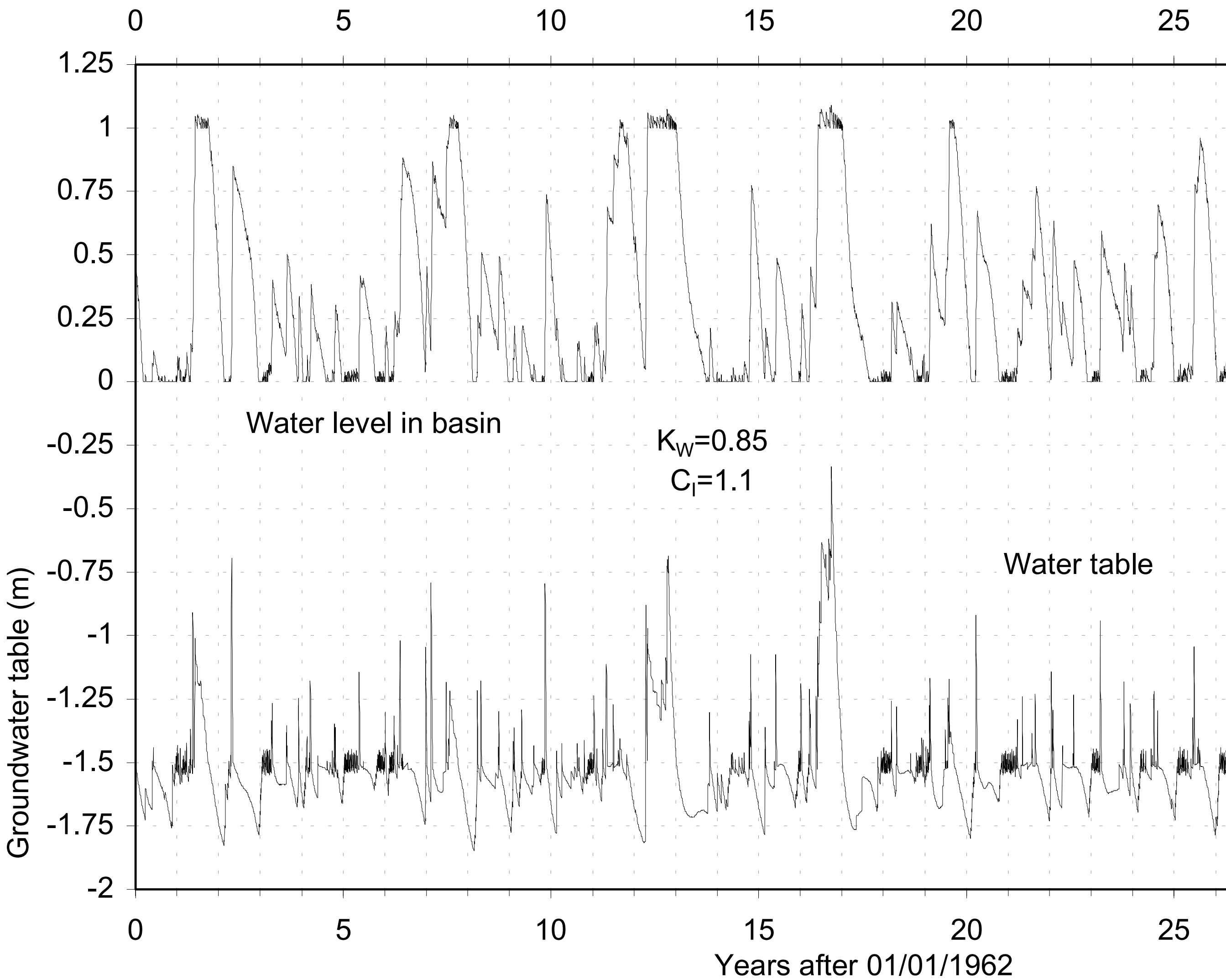


Figure 9-26. Water table depth in farm and basin water height for a 7.5% basin area

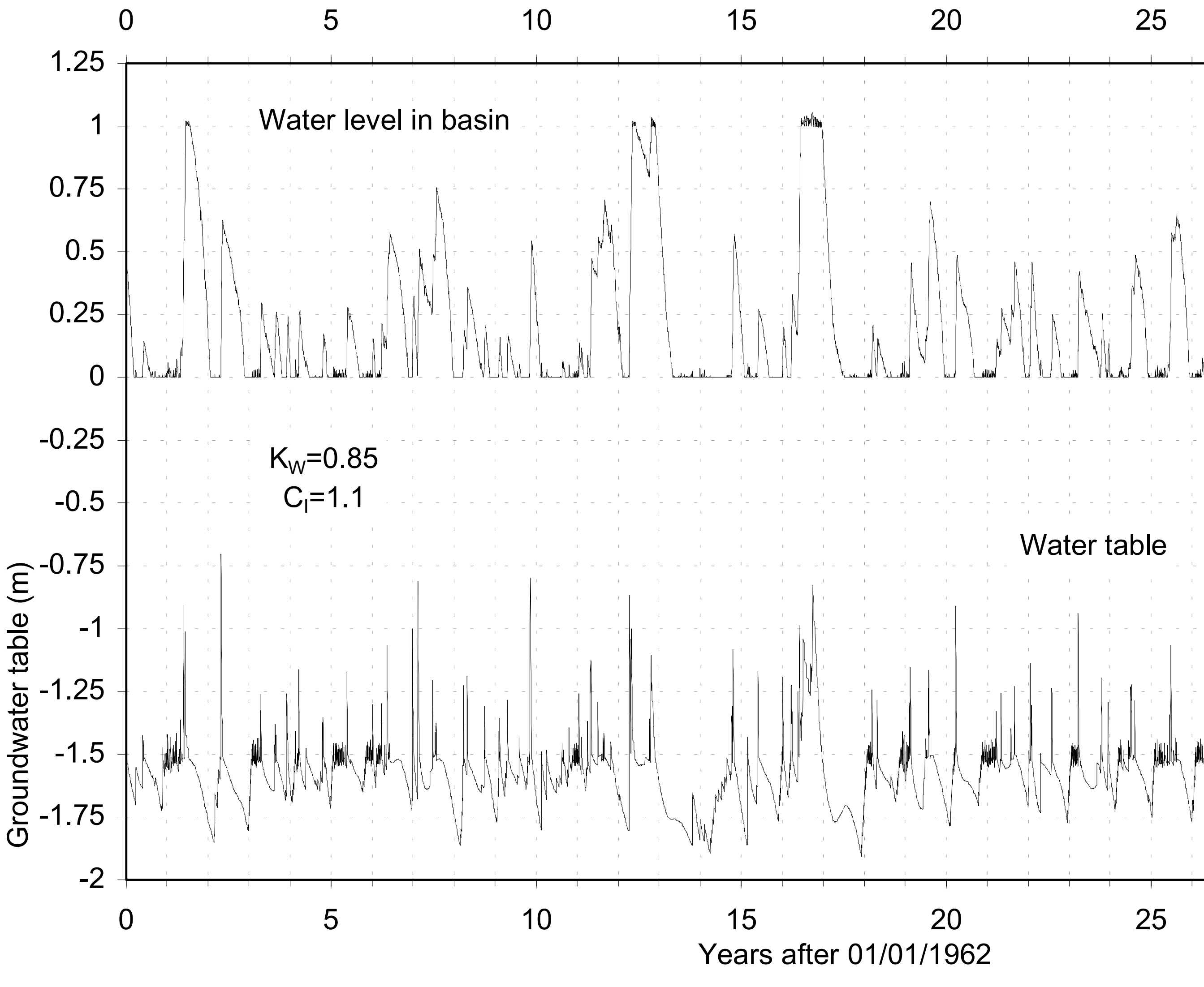


Figure 9-27. Water table depth in farm and basin water height for a 10% basin area

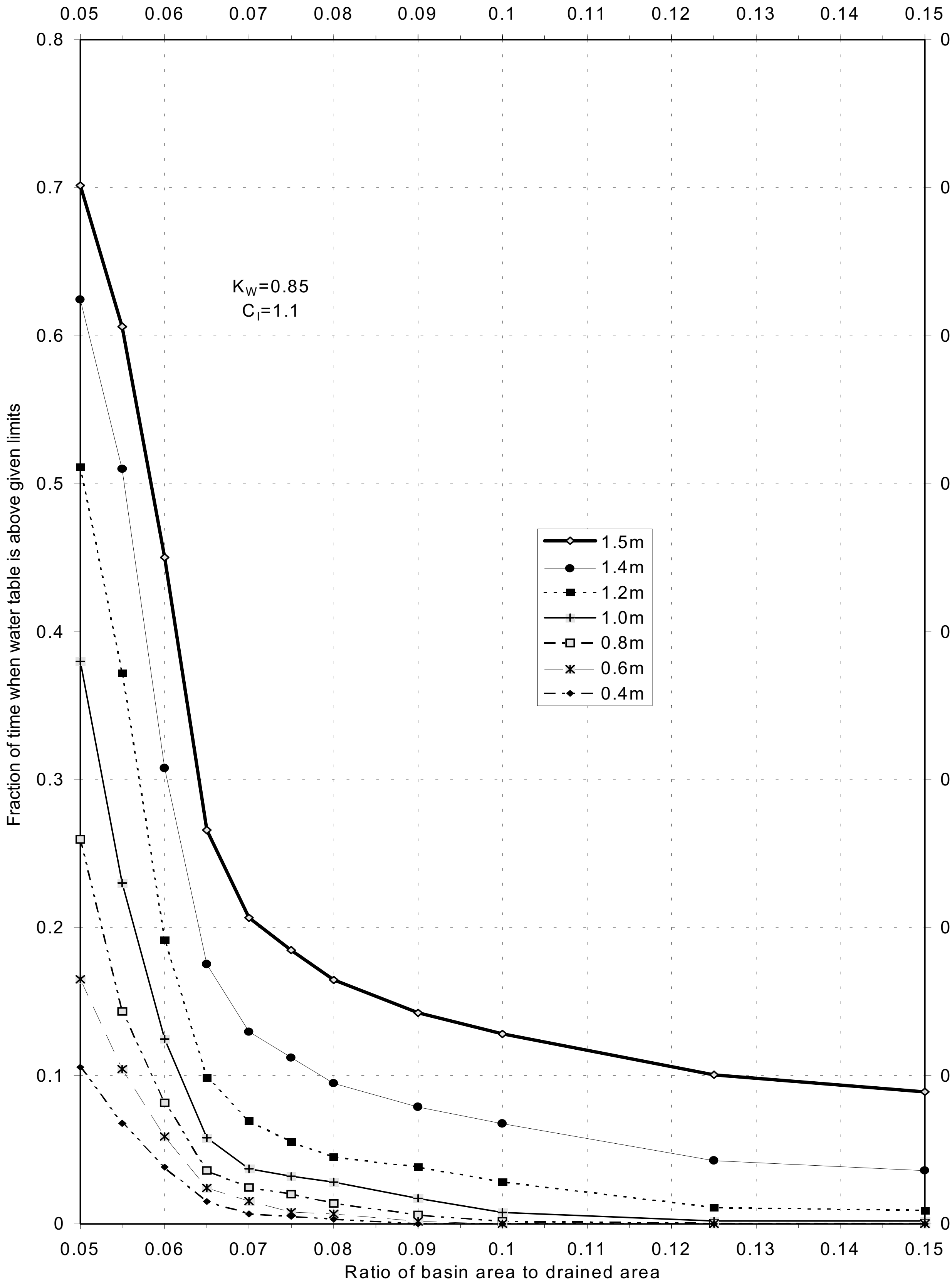


Figure 9-28. Extent of waterlogging as a function of evaporation basin area

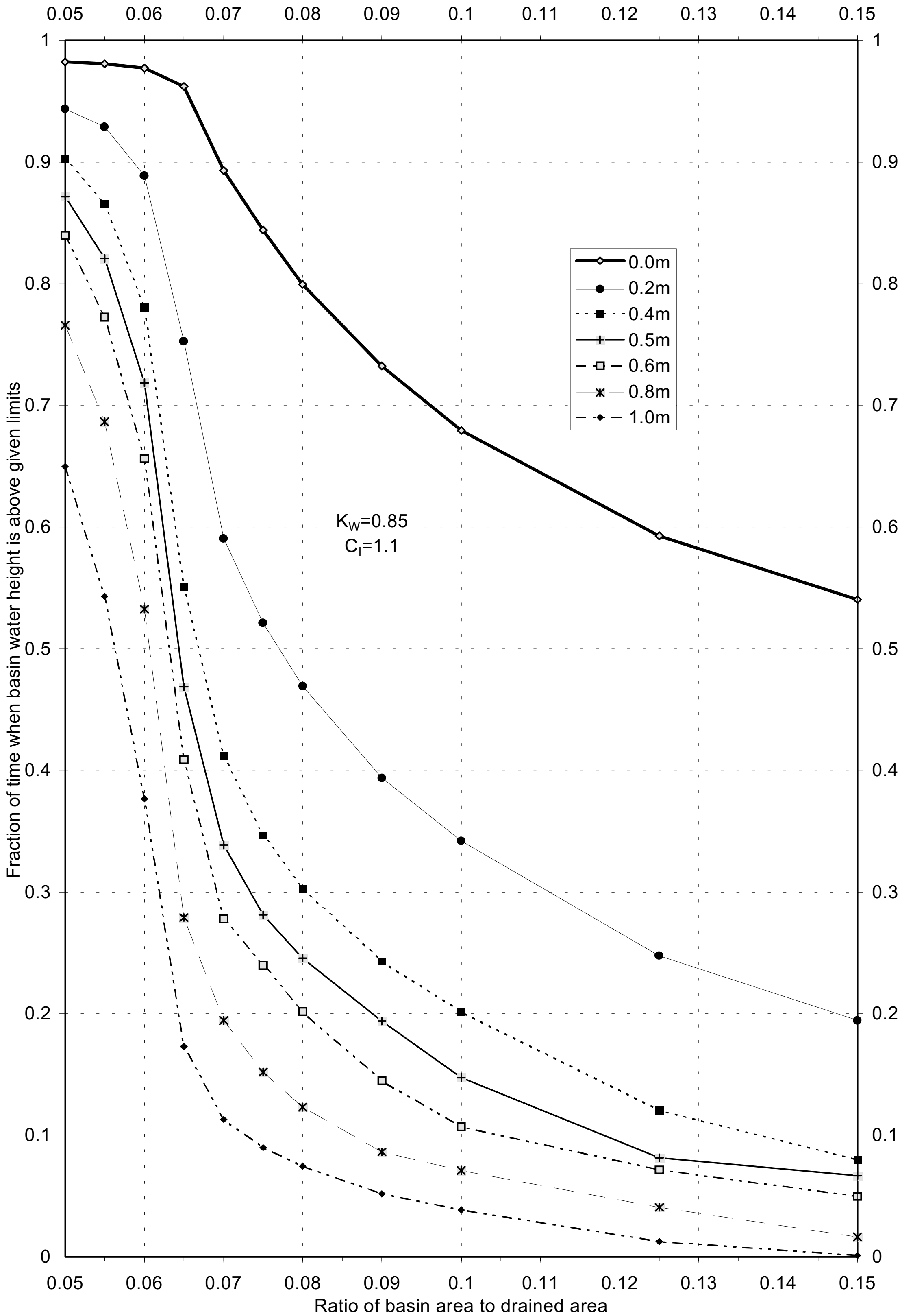


Figure 9-29. Status of basin water height as a function of evaporation basin area

9.6 Sensitivty Analysis

Four important factors in the on-farm basin system were selected for sensitivity analysis to test the model and give further insight into the system. They are irrigation efficiency C_I , farm evapotranspiration ET_C , open water evaporation coefficient K_W , and basin leakage which is represented by saturated hydraulic conductivity of the soil at the basin bottom K_{SB} . The four outputs that usefully represent the basin/farm system derived in the previous section are analysed; the water table control curve, the waterlogging control curve, the basin ponded curve and the basin full curve.

Irrigation efficiency is a key factor driving the system as can be seen from Figure 9-30 to Figure 9-33. When C_I is increased (meaning irrigation becomes less efficient) more basin area is required to control water tables at the designated level and to prevent waterlogging. Also for a given ratio of basin area, there is more time when the water table is not controlled, waterlogging occurs, the basin is ponded, and the basin is completely full. This result is to be expected, indicating that improving irrigation practice is important in reducing the area of land required for basins.

The same trends as above are also found when varying evapotranspiration, Figure 9-34 to Figure 9-36. For crops with higher ET_C demand, more irrigation is needed. If the irrigation has the same level of C_I , then more water is wasted that requires larger basin areas. The sensitivity test results for ET_C also show that when managing irrigation by ET_C , its accuracy is an influential factor. A small error in ET_C estimation (such as 20%) will cause a significant difference in water application and thus the effectiveness of the basin.

Analysis of the open water evaporation coefficient K_W, Figure 9-37 to Figure 9-39, shows that areas with high evaporation will require less basin area. This shows that evaporation basins are likely to be more efficient in hot and dry areas.

The sensitivity analysis of basin leakage shows that for small basin ratios (<9%), the time when basin has water is the same, Figure 9-42, as the basins are ponded all the time; whereas if basin ratios are increased (>9%), the time the basins are ponded is reduced. This means that for small basin ratios, there is enough drainage water to replace the water lost by leakage for a large K_{SB} , but this becomes impossible for large basin ratios. Thus, the basin becomes dry more frequently. Analysis of the basin full curve shows that for small basin ratios (<10%), the time when basin is full also declines with increasing K_{SB} , which can be explained similarly as for the basin ponded curve. However for large basin ratios (>10%), the time when the basin is full drops to a quite low level and is nearly the same for all K_{SB} .The reason for this is that it is more difficult to keep a large basin full, except during extreme rainfall periods or highly excessive irrigation that would keep the basin full even with a high K_{SB} .

In Figure 9-41, there is only a very small difference between the waterlogging curves for all three K_{SB} , with that for lining a little bit higher than for small basin ratios (<10%). The small difference shows that the waterlogging curve is insensitive to the basin leakage. It mainly plays a role in circulating the drained water between the farm and basin, with no circulation for lining, increasing with higher K_{SB} . This circulation has little effect on the waterlogging. This result is interesting in helping understand the role of the basin leakage in on-farm basin systems. It may be assumed that the salt distribution will behave differently from the waterlogging with respect to K_{SB} , which will need further investigation. The slightly higher waterlogging curve with basin lining is due to the higher basin full curve, which means there is more time when the basin is full preventing pumping.

In Figure 9-40, it can be seen that there is no difference between the water table control curves (1.5m) for small basin ratios (<8%); whereas the highest curve is with the highest K_{SB} for larger basin ratios (>8%). The reason for this is that for small basin ratios, all the basin full curves are high (>60% of the time) which makes basin storage the main limiting factor to pumping. Whereas, the opposite occurs for larger basin ratios where the maximum pumping capacity is the main constraint. Thus for the higher K_{SB} , there is a higher leakage which requires more pumping to control the water table at the same depth. Under these conditions, the drainage system is operating near full capacity and there is a greater likelihood of high water table conditions.

It should be noted that for these sensitivity tests and in the simulation runs of the next chapter, the on-farm basin systems are taken as closed systems, having no exchange with the surrounding environs. This is to isolate the system and investigate how the internal factors of the system affect its behaviour, that is to investigate the system itself. Making optimal use of the conditions within the on-farm basin system to tackle waterlogging and salinisation problems will be required for the sustainability of the system. A net flux from the system to the surrounding environment will be beneficial to the system and detrimental to the environment; and vice versa.

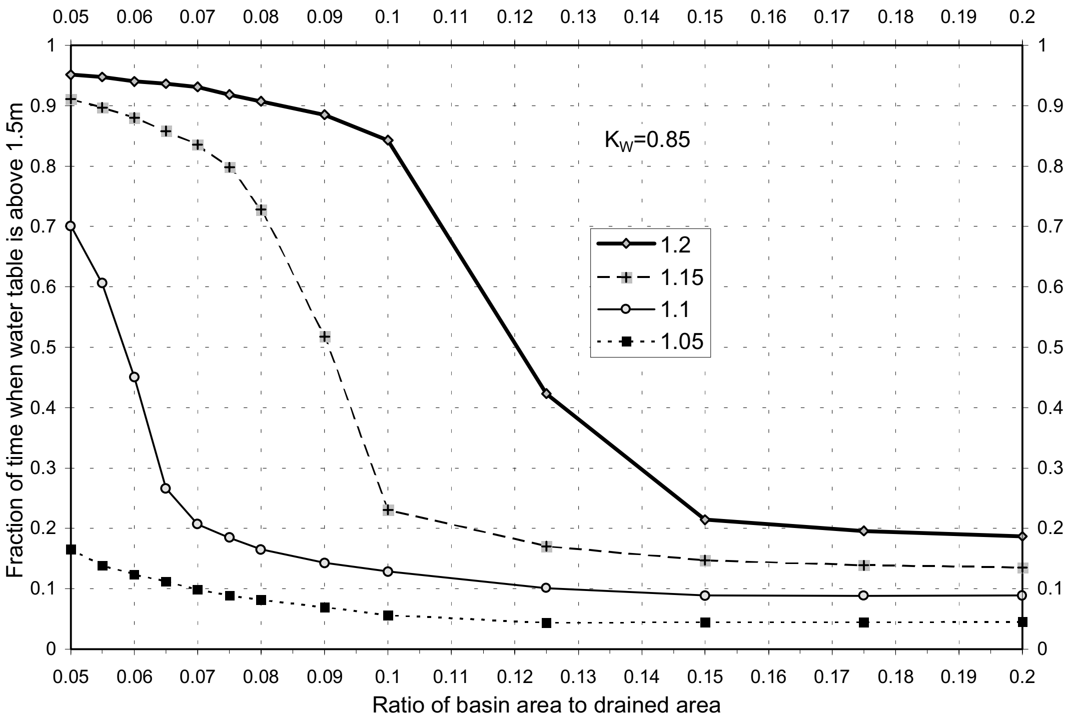


Figure 9-30. Sensitivity analysis for irrigation efficiency C_I *(1)*

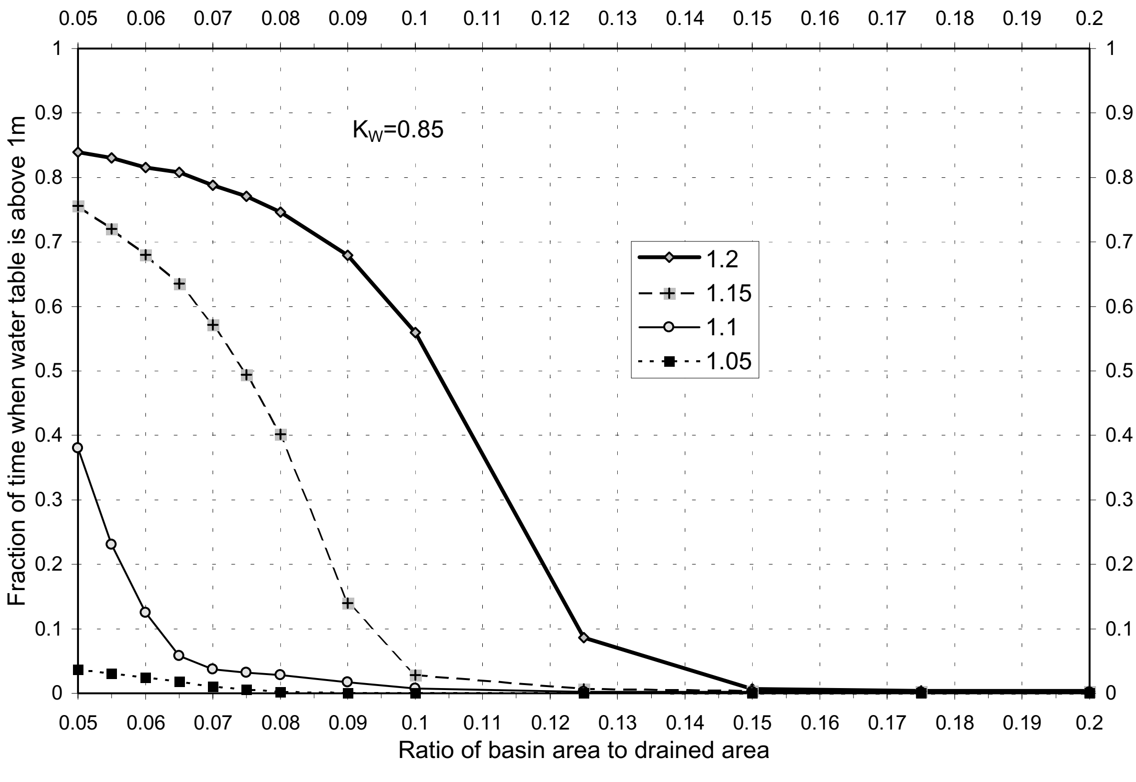


Figure 9-31. Sensitivity analysis for irrigation efficiency C_I *(2)*

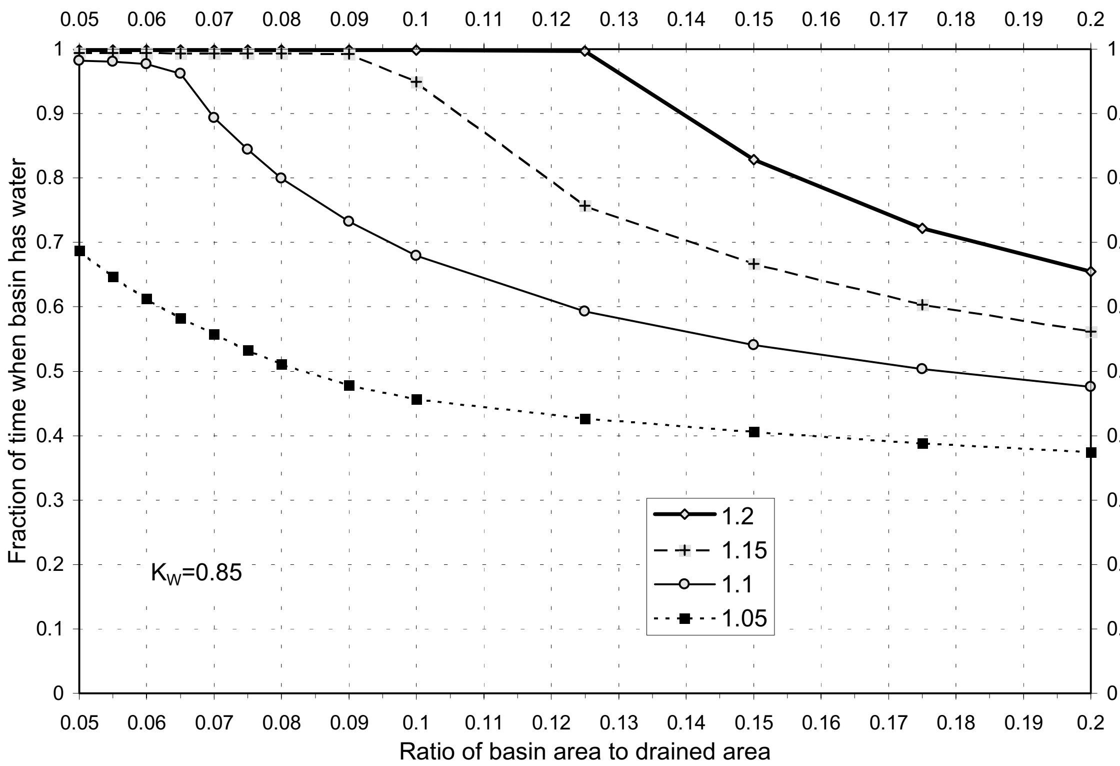


Figure 9-32. Sensitivity analysis for irrigation efficiency C_I *(3)*

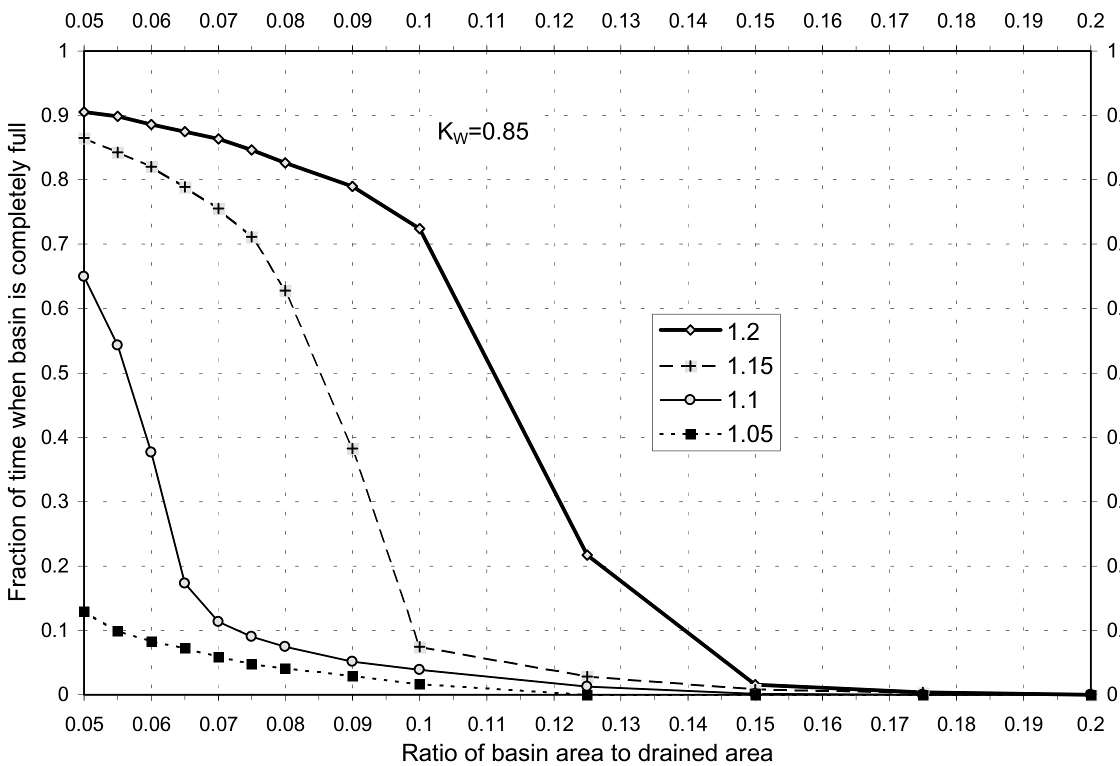


Figure 9-33. Sensitivity analysis for irrigation efficiency C_I *(4)*

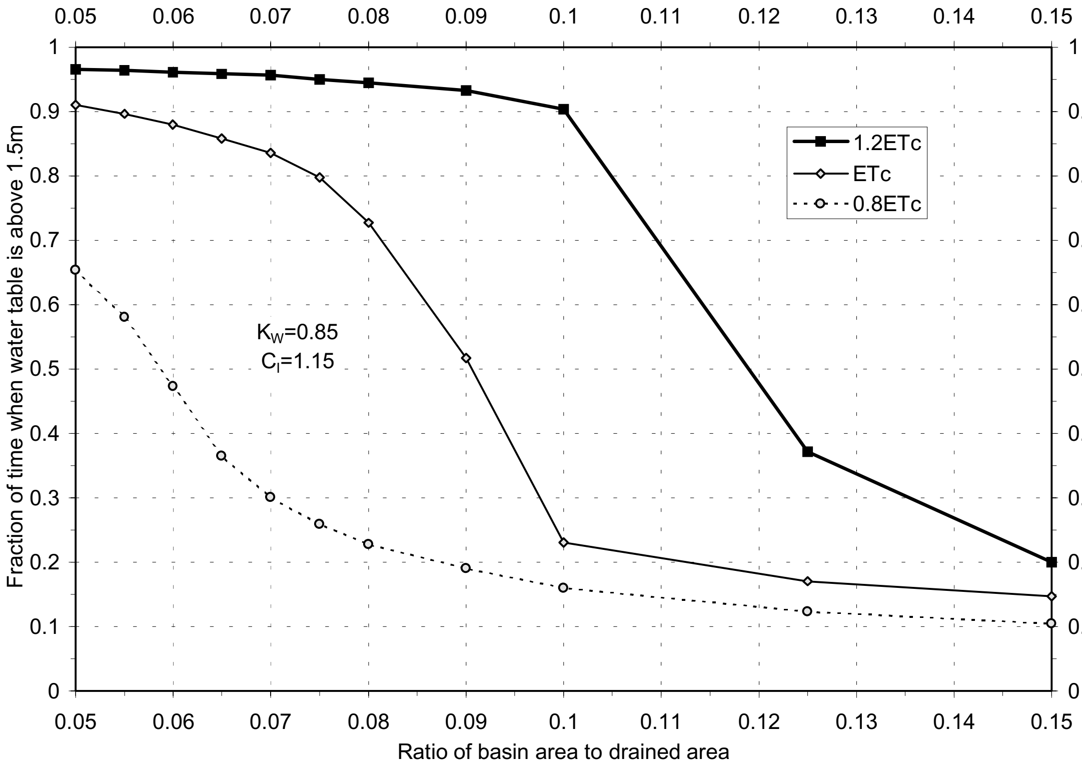


Figure 9-34. Sensitivity analysis for farm evapotranspiration ET_C *(1)*

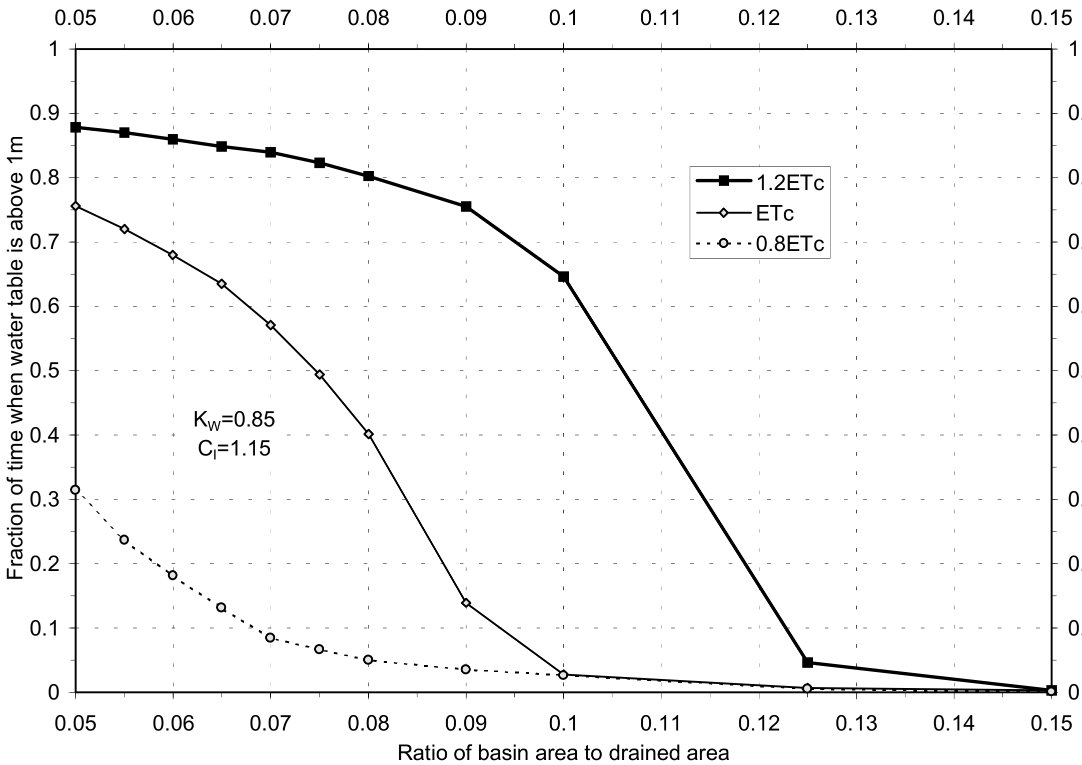


Figure 9-35. Sensitivity analysis for farm evapotranspiration ET_C *(2)*

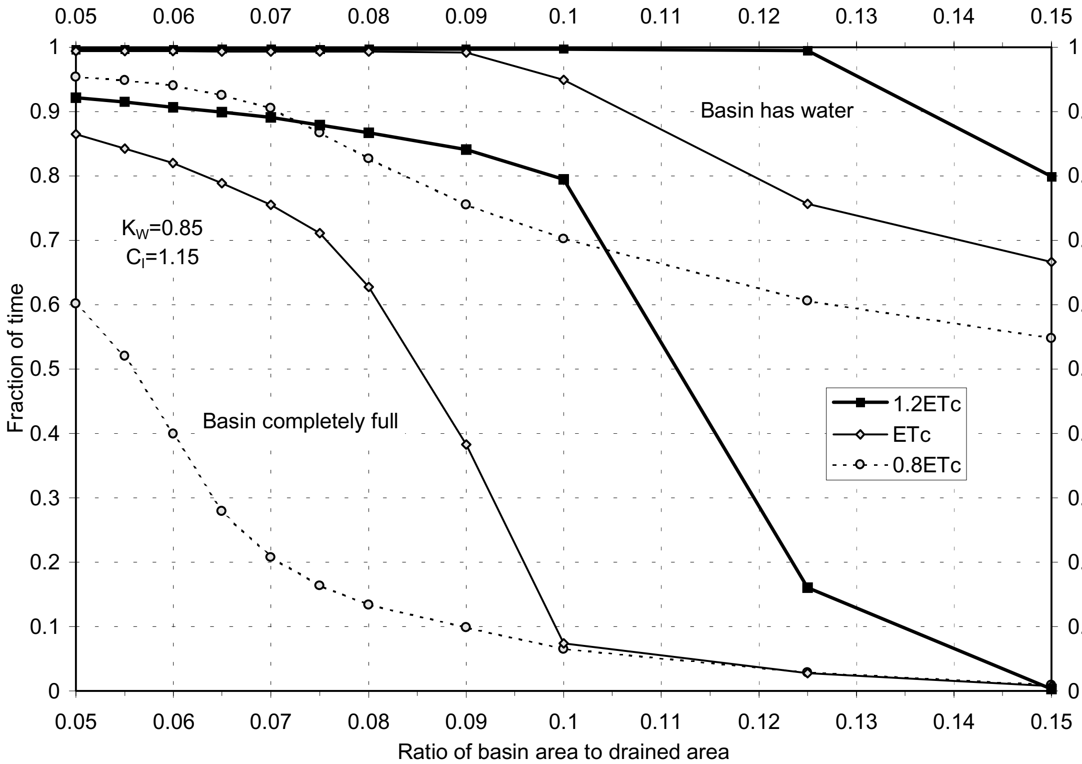


Figure 9-36. Sensitivity analysis for farm evapotranspiration ET_C *(3)*

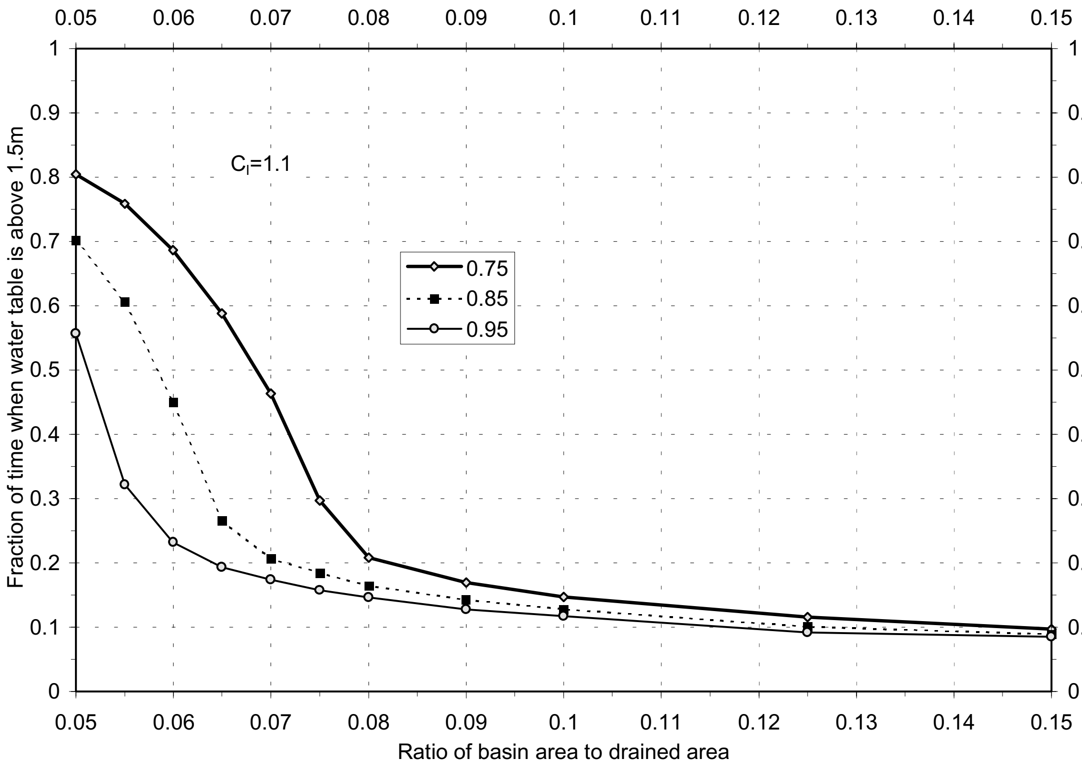


Figure 9-37. Sensitivity analysis for open water evaporation coefficient K_W *(1)*

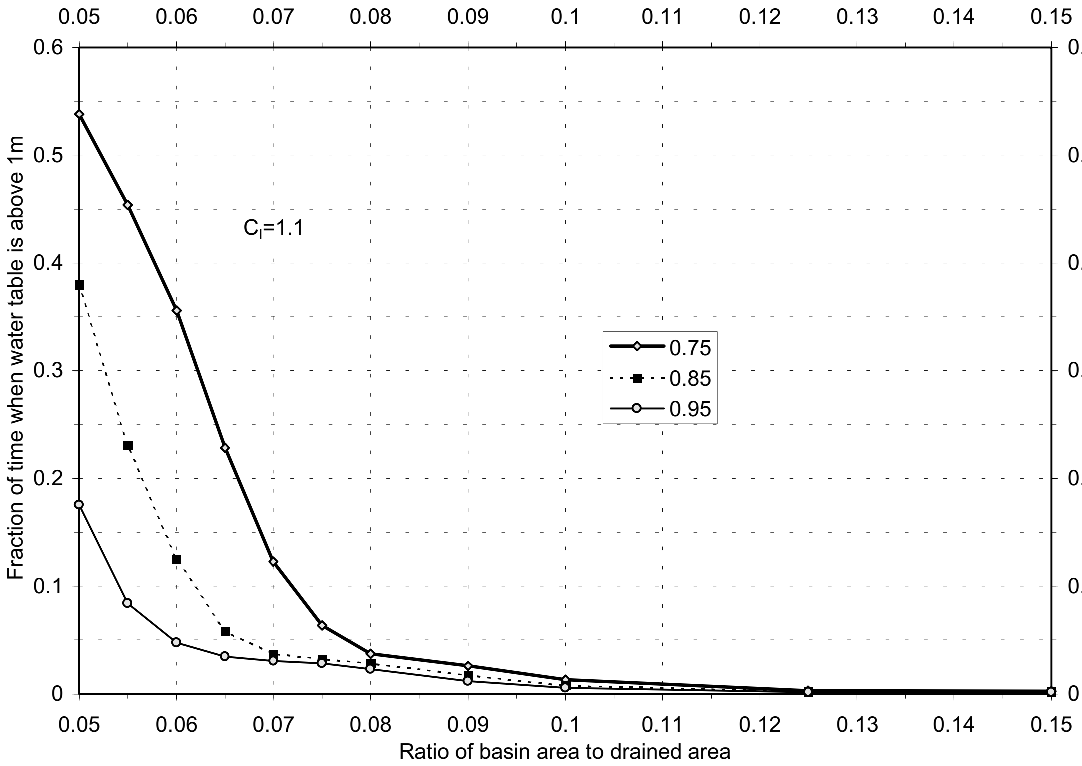


Figure 9-38. Sensitivity analysis for open water evaporation coefficient K_W *(2)*

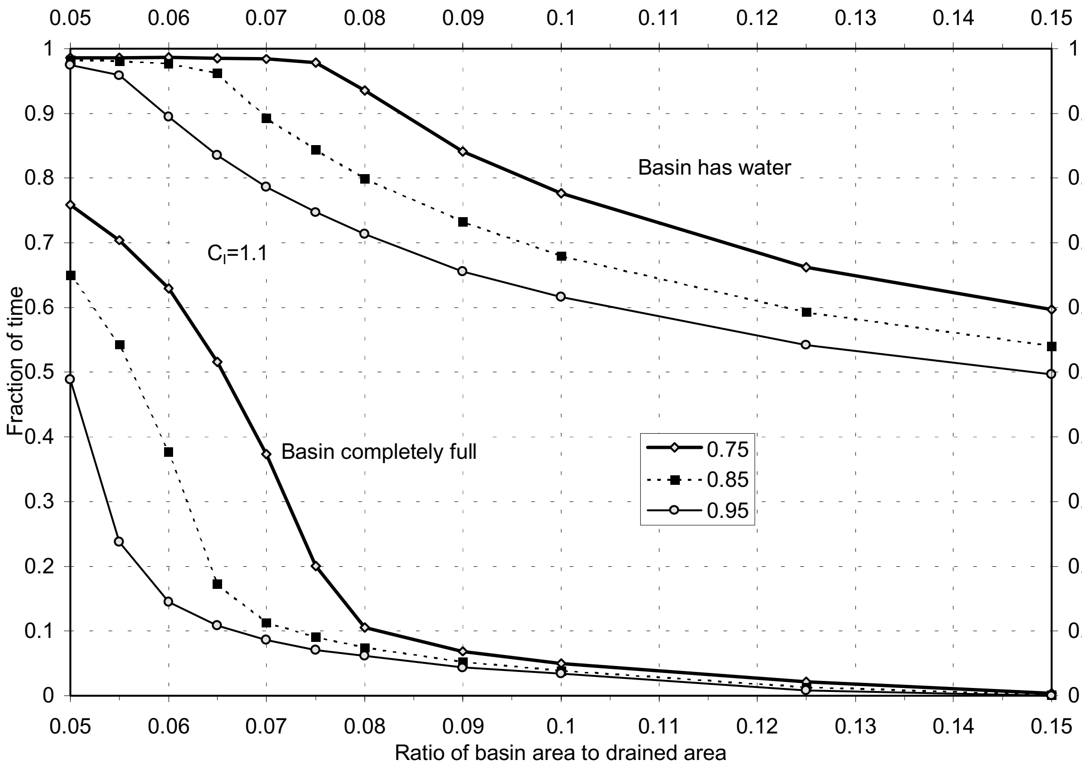


Figure 9-39. Sensitivity analysis for open water evaporation coefficient K_W *(3)*

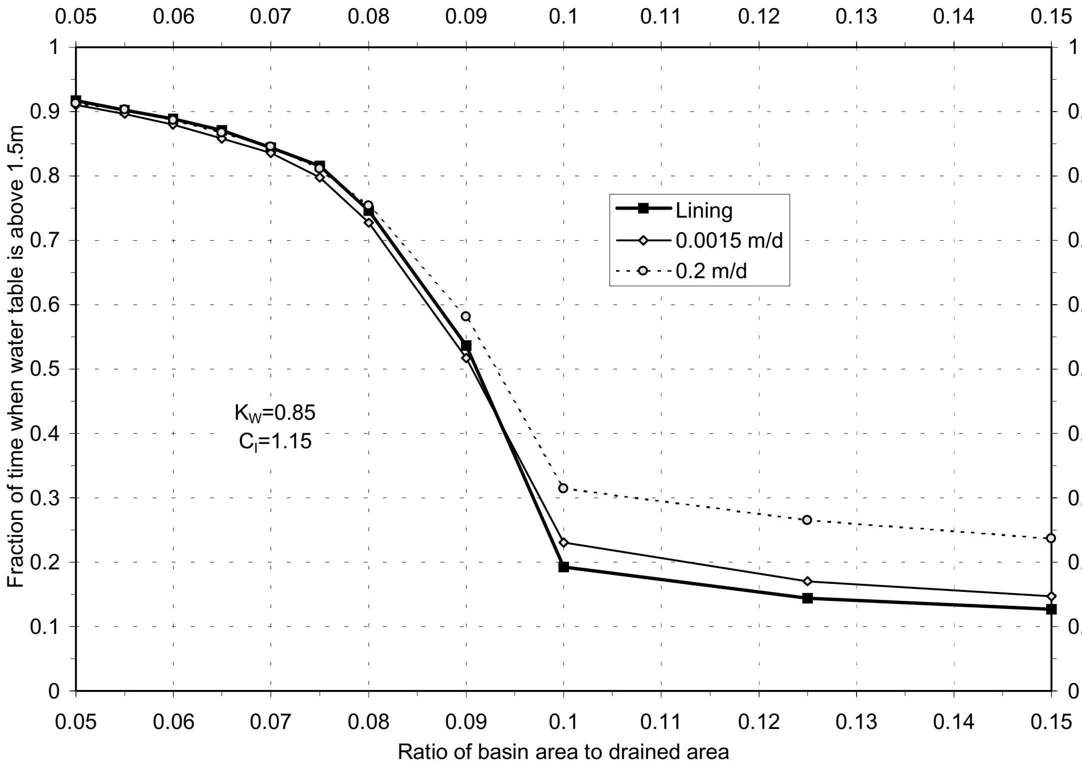


Figure 9-40. Sensitivity analysis for saturated hydraulic conductivity of the soil (K_{SB}) at basin bottom (1)

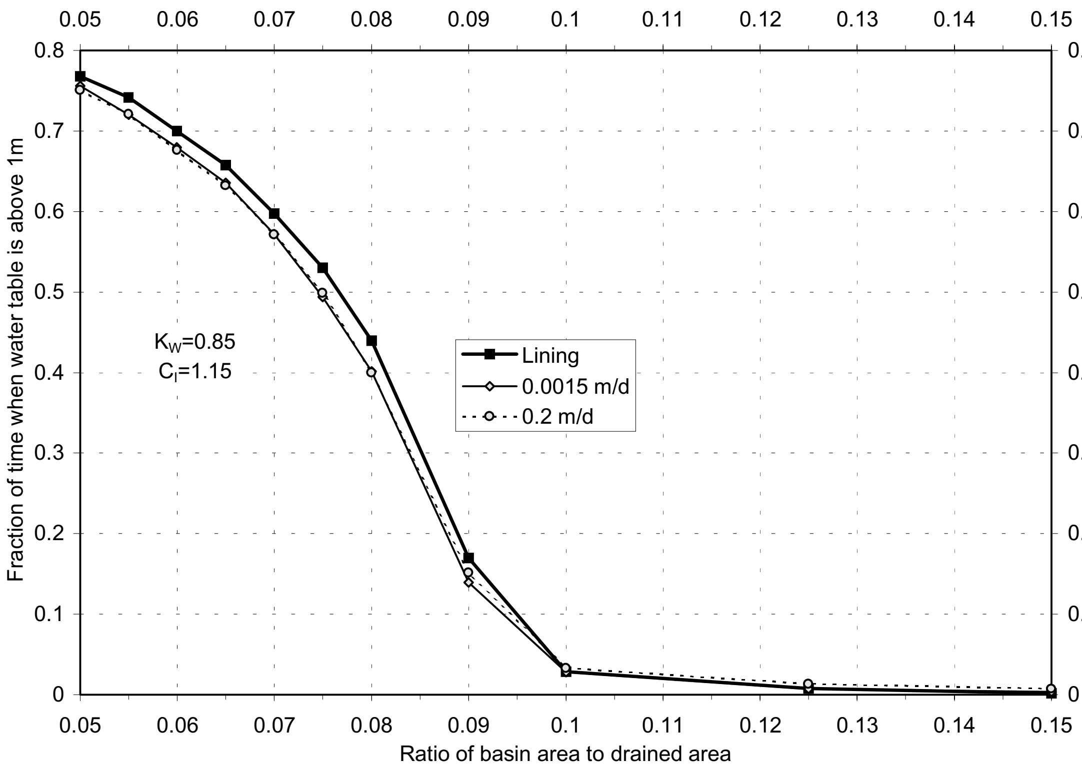


Figure 9-41. Sensitivity analysis for saturated hydraulic conductivity of the soil (K_{SB}) at basin bottom (2)

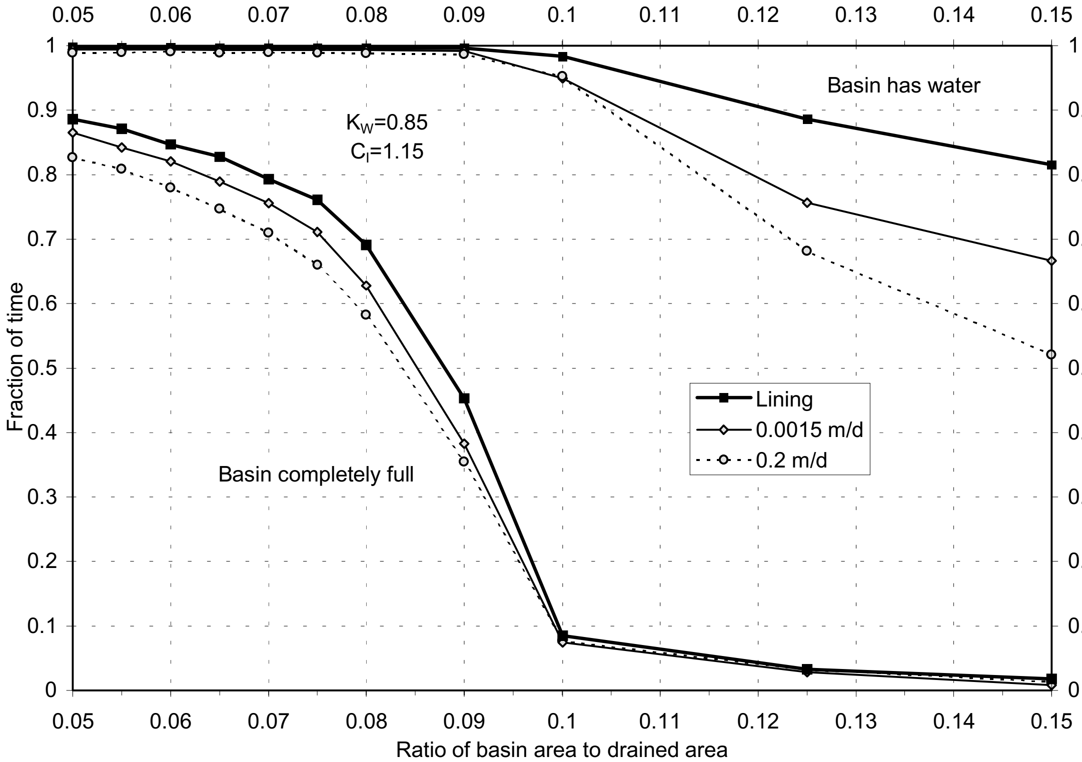


Figure 9-42. Sensitivity analysis for saturated hydraulic conductivity of the soil (K_{SB}) at basin bottom (3)

10. Simulations and Discussion

To examine management and design options for on-farm evaporation basins and the subsurface drainage system, several scenarios are tested. The basic parameters are based on those used in section 9, except for a 1.15 irrigation efficiency (C_I) and any other changes specially set.

10.1 Water Table Control Depth

In Figure 10-1, there is little difference between the waterlogging curves for the water table control depths ranging from 1.25m to 2m; but the 1m curve is clearly higher than the others. This shows that in order to prevent waterlogging, the water table control depth (H_{FA}) should beset deeper than the defined waterlogging depth (H_{WL}). This is reasonable in that some volume of storage from H_{WL} down to H_{FA} in the soil is required to temporarily store water before the drainage system removes it.

In Figure 10-2, farm pumping increases steadily with the basin ratio to 0.1, which is also a change of rate point in the waterlogging curve. After 0.1, the pumping decreases gradually and tends to stabilise. The pumping is only slightly different between the water table control depths. The reason for this is that for small ratios, the pumping is significantly restricted by the rate of evaporation at the basin. This is seen in Figure 10-4 where the fraction of time when basin has water is nearly 1 for all H_{FA} , which means nearly the same amount of basin water evaporation. Thus the farm pumping expressed on basin area is relatively static for ratios less than 0.1 and little difference exists between the different H_{FA} at this stage, Figure 10-3. For the farm area, increasing the basin area allows more farm pumping, which therefore improves the farm water table status.

For basin ratios above 0.1, the farm water table is maintained at a deeper level, Figure 10-1. The head difference above the drain becomes the main factor in controlling the pumping. With increasing basin area this head difference is reduced and thus the farm pumping.

In Figure 10-2, it can also be seen that in terms of making full use of the subsurface drainage system, there exists an optimal basin ratio. In this figure, the ratio 0.1 has the largest farm pumping. Above this point the drainage system becomes less efficient as less water needs to be removed from the farm water table.

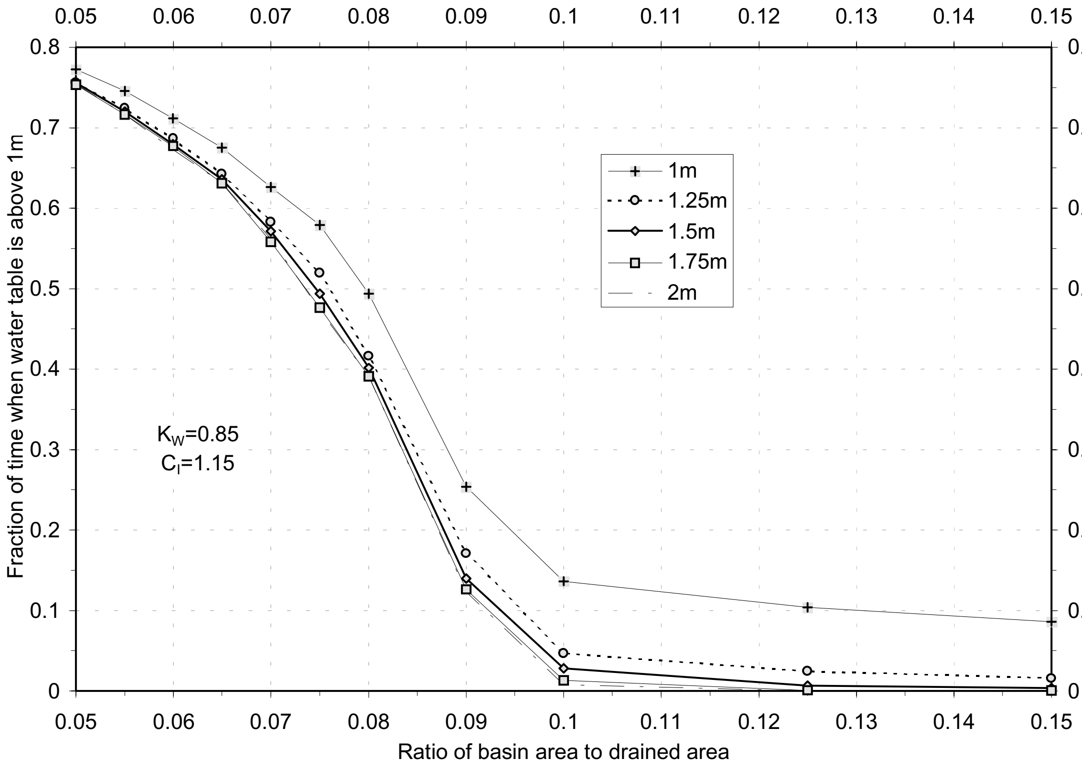


Figure 10-1. Extent of waterlogging for different water table control depths

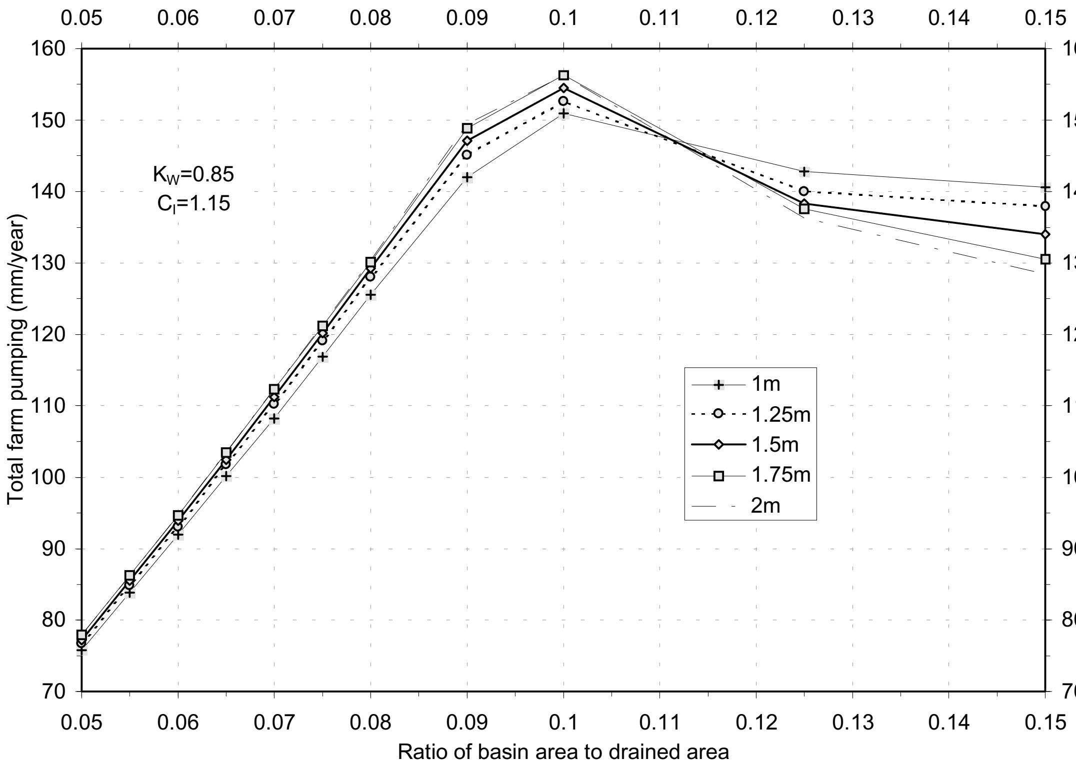


Figure 10-2. Farm pumping for different water table control depths

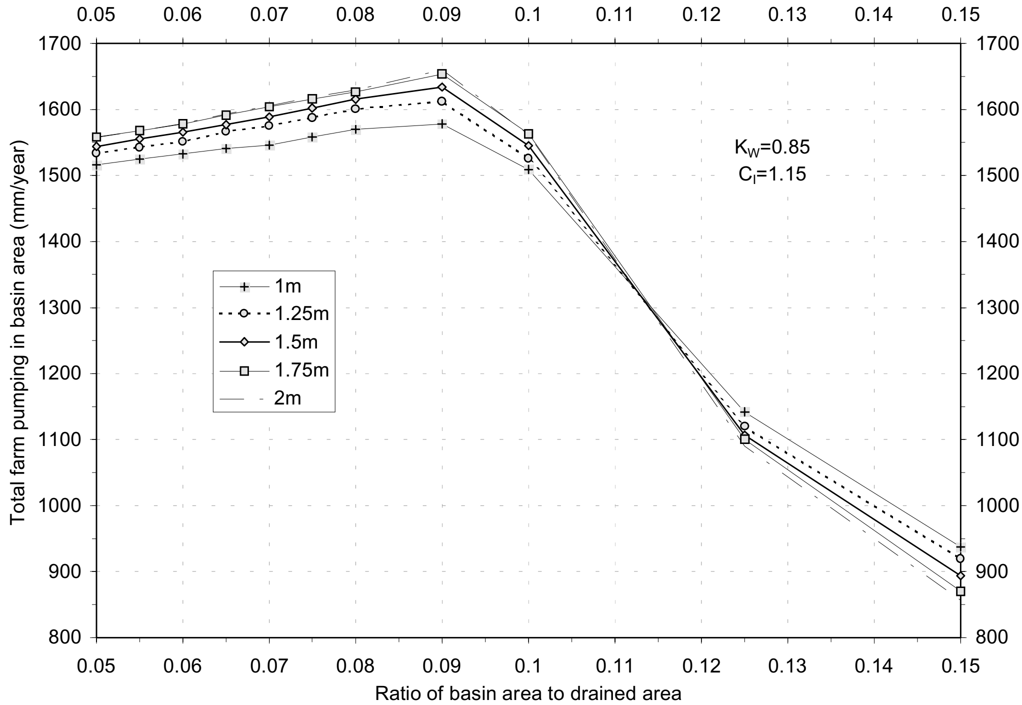


Figure 10-3. Farm pumping expressed on basin area for different water table control depths

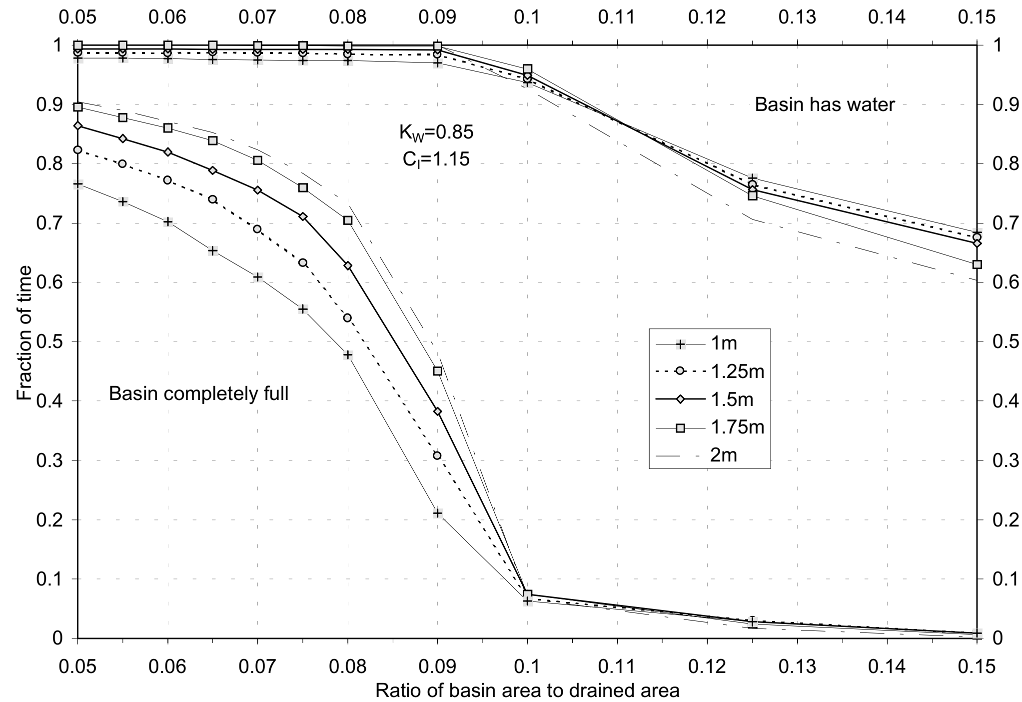


Figure 10-4. Status of basin water height for different water table control depths

10.2 Irrigation Management

Simulations with three soil water deficits D_{WC} (25, 50 and 75 mm) were carried out, Figure 10-5 to Figure 10-8. There is only a small difference between the water table control curves, waterlogging curves, farm pumping curves, basin ponded curves and basin full curves. This shows that under normal growing conditions of crops, the irrigation amount applied each time and thus the irrigation frequency has only a small effect on the water balance. Matching the application to the deficit is the most important part of irrigation management as shown in the sensitivity analysis of section 1.1.

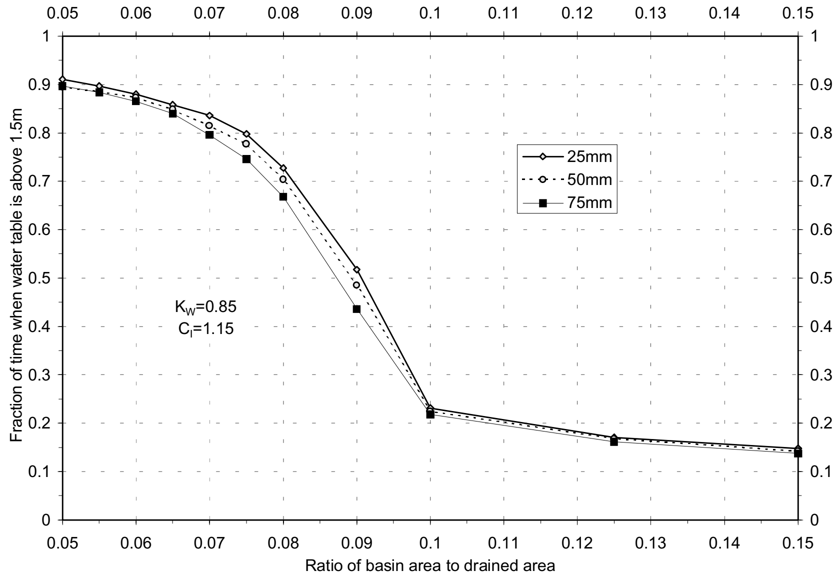


Figure 10-5. Extent of water table control for different irrigation application criteria

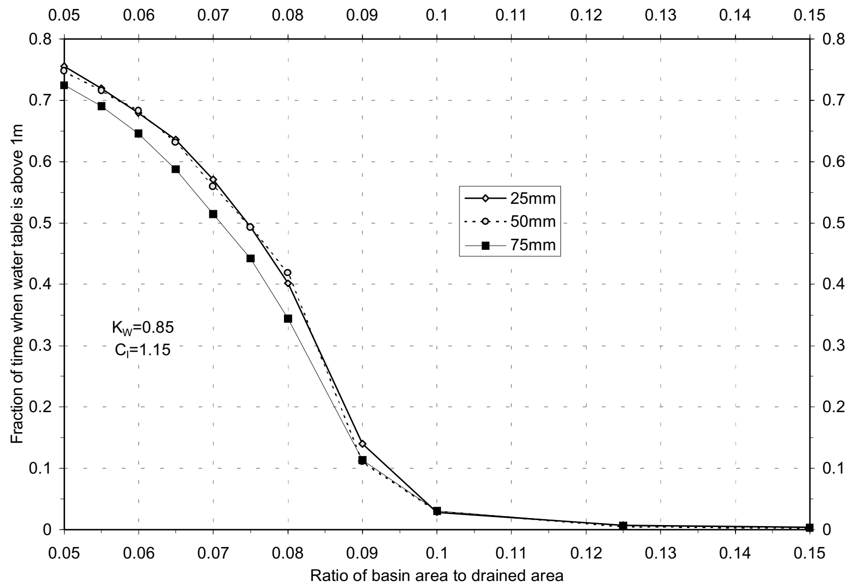


Figure 10-6. Extent of waterlogging for different irrigation application criteria

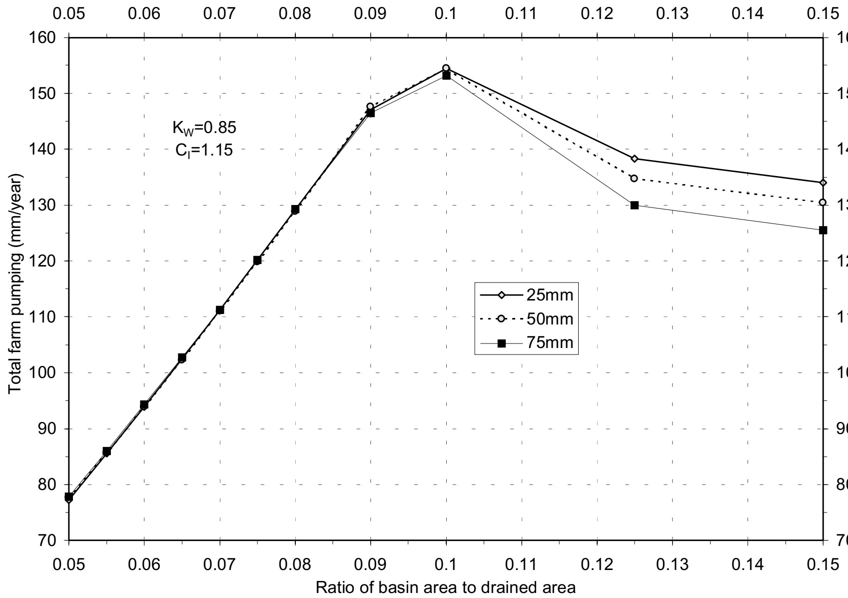


Figure 10-7. Farm pumping for different irrigation application criteria

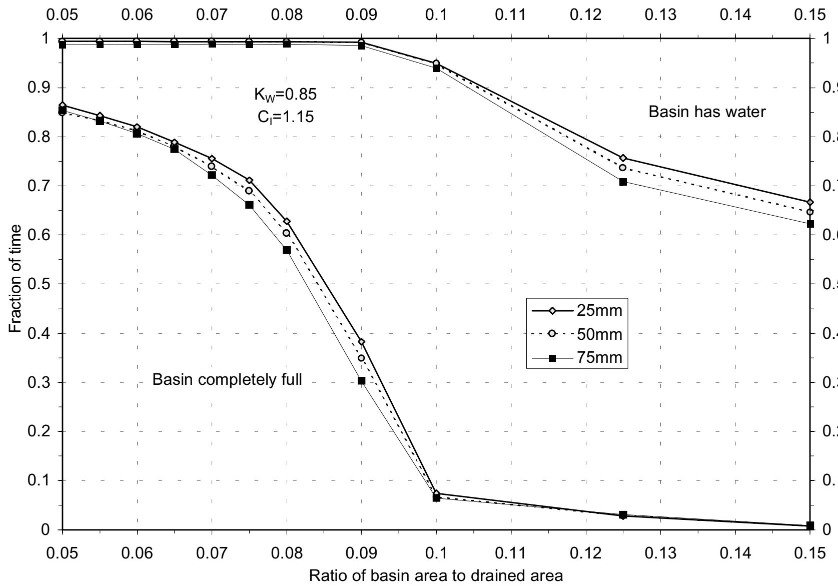


Figure 10-8. Status of basin water height for different irrigation application criteria

10.3 Basin Leakage

Figure 10-9, shows that the leakage condition at the basin bottom significantly affects the pumping required. Basin leakage promotes the circulation of water between the basin and farm. This would reduce the salt accumulation in the basin, but has little effect on the waterlogging in the farm, which has been tested in section 1.1.

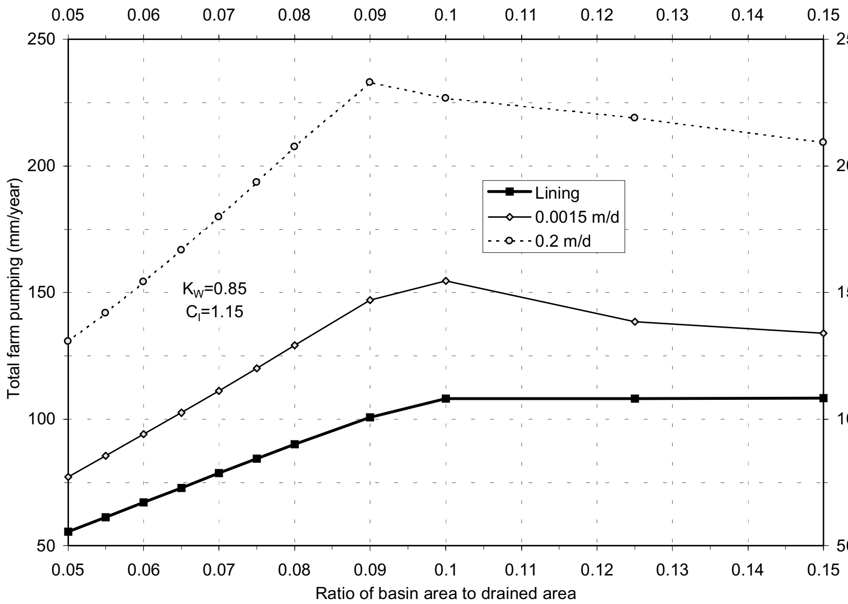


Figure 10-9. Farm pumping for different basin leakage

10.4 Basin Depth

In Figure 10-10 and Figure 10-11, it can be seen that with increasing basin depth, there is an improvement in the water table and waterlogging. The greatest improvement occurs by increasing from 0.5 m to 1 m, increasing from 1 m to 1.5 m has less effect.. Thus increasing basin depth is useful up to a point, after which it is better to increase the basin area. In Figure 10-12 and Figure 10-13, there are also differences between the pumping, basin ponded and full situations for different basin depths.

Table 10-1 shows the relative importance of basin depth to basin area. Increasing basin volume by increasing the depth has a minor effect on waterlogging. A three fold increase in depth results in only a marginal reduction in waterlogging from 0.56 to 0.48. However, increasing basin volume by increasing area has a major effect on waterlogging. A three fold increase in area results in a significant decrease in waterlogging from 0.76 to 0.01. For any particular basin volume a design with shallow depth and large area is more effective than a smaller area with greater depth. Thus, increasing the basin area is far more efficient than increasing the basin depth in controlling waterlogging.

Table 10-1. Fraction of time when waterlogging occurs for different basin settings

Same area (0.075A_F), different depth		Same depth (1m), different area		Same volume		
Depth (m)	Fraction	Area	Fraction	Depth (m)	Area	Fraction
0.5	0.56	0.15A_F	0.01	0.5	0.15A_F	0.03
1	0.49	0.075A_F	0.49	1	0.075A_F	0.49
1.5	0.48	0.05A_F	0.76	1.5	0.05A_F	0.75

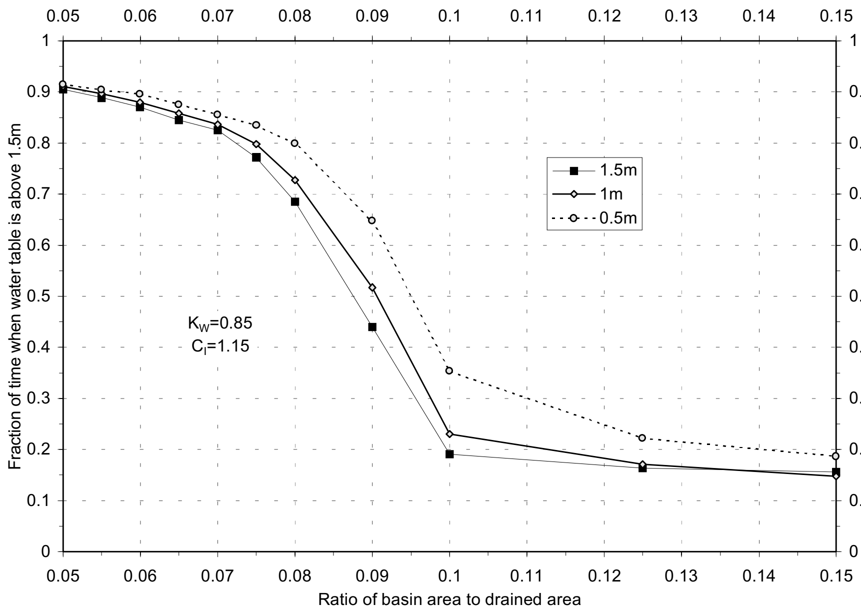


Figure 10-10. Extent of water table control for different basin depths

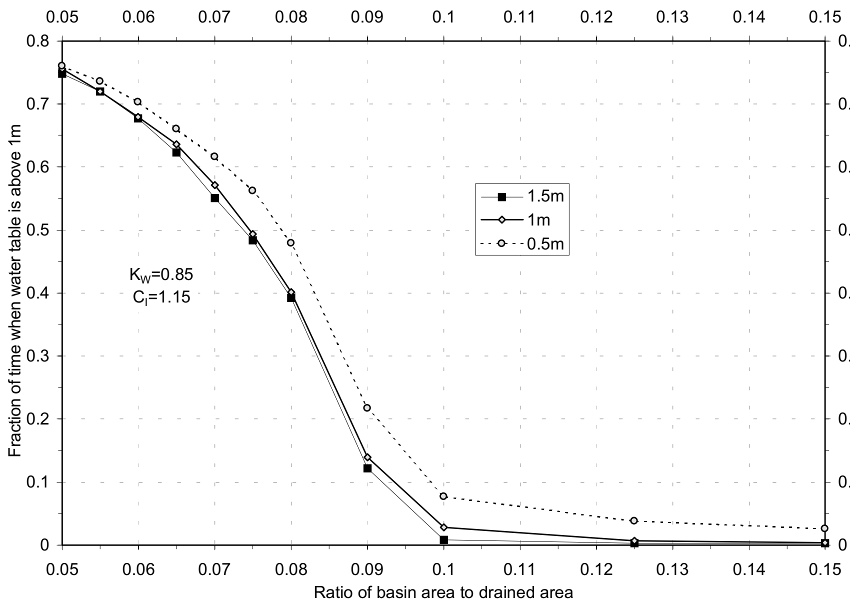


Figure 10-11. Extent of waterlogging for different basin depths

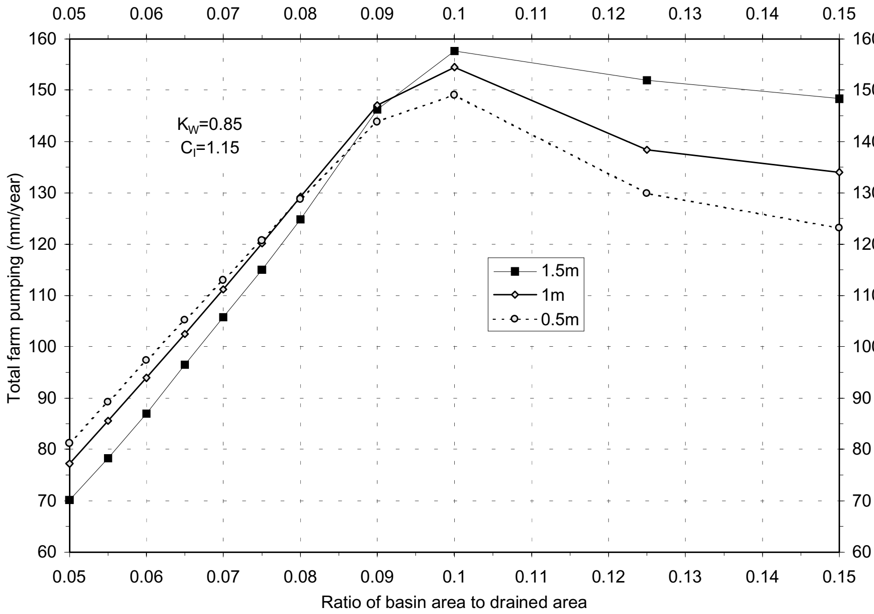


Figure 10-12. Farm pumping for different basin depths

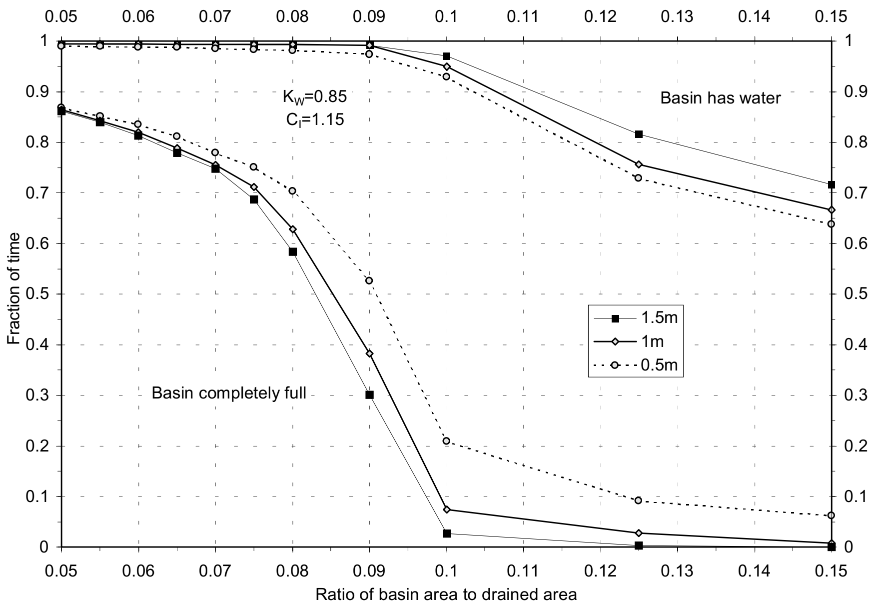


Figure 10-13. Status of basin water height for different basin depths

11. Conclusions

This study has shown that a farm with evaporation basin is a complex hydrological system. This work has been able to identify, understand and model the linkages in the system. The key findings from the work are:

Model development and testing

§ An understanding of the hydraulic relationships in the farm and evaporation basin system has been obtained, including the influence of management decisions on the biophysical processes, which provides the basis for a sound physical model. This has allowed the farm and evaporation basin system to be analytically depicted such that a mathematical model of equations and expressions can adequately simulate the actual hydrological processes. The Basinman computer model provides for the first time a tool to simulate a linked farm and evaporation basin system, revealing the complicated relationships between the farm and evaporation basin and the key controlling factors.

§ Model simulations have shown the model to be capable of representing the many varied basin and farm hydraulic conditions experienced in reality, e.g. farm saturated or unsaturated, basin dry, basin ponded, basin soil saturated or unsaturated, controlled irrigation, flood irrigation. Testing against field data in the MIA has shown that the model can simulate actual conditions reasonably well and comparisons with the more sophisticated Destiny model have been good.

System sensitivity

§ Using long term weather data sets, simulations show that with closed boundary conditions, the system behaviour in terms of water distribution is greatly controlled by external factors such as meteorological evaporative capability, rainfall and irrigation efficiency. Whereas the internal factors are of lesser importance. For instance, basin leakage only accelerates circulation of water within the system, with little effect on waterlogging control, and the water table depth settings for controlling pumping have even less effect on the system. The modelling results also show that the basin area is far more important than the basin depth in controlling waterlogging. For any given storage volume a large area with shallow depth is more useful than a small area which is deeper.

Parameters for quantitative analysis of a farm and basin system

- To simplify quantitative analysis of a farm and basin system several useful parameters have been developed. The 'water table control curve' which is the fraction of time the water table is above the drainage base gives an indication of how well the original water table control criterion is fulfilled. The 'waterlogging control curve' gives an indication of the farm waterlogging status and thus allows for an analysis of the trade off between the cost of increasing basin area and the subsequent benefits of reduced farm waterlogging. The 'basin ponded curve' and 'basin full curve' indicate the effective utilisation of the basin in evaporating drainage water. These parameters can be assessed on a yearly or seasonal basis with the model and thus enable a quantification of design and management scenarios.

Design and management

- The key to an efficient farm with evaporation basin system is to optimise the basin area such that the basin area is large enough to reduce waterlogging in the farm to an acceptable level, without being so large that the basin evaporative capacity is under utilised. Thus, the appropriate basin to drained area ratio is better selected from the most 'efficient' range of basin ratios or around the critical value. Using this principle, the basin is also most efficient in evaporating drainage. The appropriate basin ratio is highly dependent upon the required extent of protection for the cropped land, irrigation efficiency (C_I) and open water evaporation capability (K_W). For example, if water tables are only allowed to be less than 1m for 10% of the time and $C_I=1.1$, $K_W=0.85$, then this ratio is about 6.5% for the modelled farm in the MIA. In reality the percentage of land would be greater than 6.5% as typical values of C_I are greater than 1.1.

Further work

- Further work with the BASINMAN model may consider applying some boundary conditions such as a regional piezometric head from which a hydraulic gradient into or out of the farm could be estimated. It would also be useful to estimate a crude salt balance using the water balances developed here. Areas for more analysis to further optimise the farm and basin system would be to consider the farm waterlogging status on a seasonal basis related to the crop growth conditions.

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