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# A soil water and groundwater SIMulation model: SWAGSIM

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## Abstract

Recent estimates indicate that one-half of the existing irrigation areas around the world have shallow water tables, and require careful water management practices to prevent reduced productivity due to waterlogging and secondary salinisation. Hydrologic processes affecting shallow water tables occur continuously in both the saturated and unsaturated soil phases, and are influenced by climate agronomy and hydrogeology. We have developed a soil, water and groundwater SIMulation model (SWAGSIM) that aims to facilitate evaluation of shallow water table management options with minimal data and computing requirements. It is optimised for the Microsoft Windows operating system. In this paper, we describe the processes modelled within SWAGSIM, and its availability to potential users. SWAGSIM has been successfully used to determine the impact of rice growing in the Murrumbidgee Irrigation Area (MIA) of New South Wales, to evaluate the feasibility of using shallow groundwater pumps to control water tables in the MIA, to evaluate subsurface drainage options for the Mead Ridge project area in Victoria, and to evaluate groundwater discharge into the Hunter River of New South Wales. Copyright © 1996 Elsevier Science Ltd

*Keywords:* Irrigation; simulation; water table management; drainage; model

**Software availability**

| | |
|---|---|
| Program title: | SWAGSIM—Soil Water and Groundwater SIMulation |
| Developers: | C Vision Pty Ltd |
| Contact address: | Mirvac Trust Building, 185 Elizabeth Street, Suite 320, Sydney, NSW 2000, Australia |
| First available | November 1995 |
| Hardware: | IBM PC or compatible; graphic card VGA; Operating system: Microsoft Windows 3.1 or later; Required memory 4 Mb RAM. |
| Software required: | Program requirements, Microsoft Access 2.0; program size, requires 2 MB hard disk storage; user's guide available. |
| Cost: | Available as proprietary software from C-Vision for A$ 800. |

## 1. Introduction

Rising groundwater levels are now commonly observed in the irrigation areas of many countries. Rhoades and Loveday (1990) have estimated that one-half of the existing irrigation areas around the world have shallow water tables. In older irrigation areas such as the Murrumbidgee Irrigation Area (MIA) in New South Wales, Australia, over 80% of the landscape has water tables within 2 m below the ground surface. The presence of water tables in such close proximity to the ground surface greatly increases the potential for waterlogging and salinisation, and poses difficulty for soil management. In order to prevent continuing degradation of agricultural production and the environment, it is necessary to understand and quantify the physical processes affecting water table fluctuation in a shallow water table environment.

Groundwater models have traditionally been used to predict water table fluctuations in unconfined aquifers (e.g. PLASM by Prickett and Lonnquist, 1971; MODFLOW by McDonald and Harbaugh, 1984). Conceptualisation of recharge and discharge to and from the unconfined aquifer varies in these models. PLASM requires recharge and discharge fluxes to be estimated externally for input at each time step. MODFLOW requires external estimation of recharge for use as input. Estimation of discharge from the water table requires input of the maximum rate at which capillary upflow could take place, the water table depth for capillary upflow to be at its maximum, and water table depth at which capillary upflow will cease. Therefore, it is difficult to account for surface (land, crop and water) management practices that determine vertical fluxes to the water table in irrigation areas in these models.

In response to such deficiencies, a soil water and groundwater SIMulation model (SWAGSIM) has been developed. This model is conceived specifically for irrigation areas with shallow water tables, and is designed to minimise data requirements.

SWAGSIM models evapotranspiration from the root zone, recharge to water table aquifer through soil matrix and cracks, recharge from evaporation basins, discharge from the water table aquifer as capillary upflow, discharge from mole drains, tile drains and pumps, lateral groundwater flow within the water table aquifer, leakage between the water table aquifer and an underlying saturated confined aquifer, and the interaction between surface channels and/or rivers and the water table aquifer. It is capable of modelling spatial and temporal fluctuations of shallow water tables, identifying recharge and discharge zones within irrigation areas, and assisting the evaluation of drainage options at field and regional scale.

Conceptually, similar modelling approaches have been adopted by Pikul *et al.* (1974) and Abbott *et al.* (1986a,b). They adopted numerical solutions for the unsaturated flow equation, and a common model grid for processes within the soil profile and in the water table processes within the soil profile and in the water table aquifer. In SWAGSIM, a transient analytical solution for the unsaturated flow equation is adopted, with separate grids used for processes within the unsaturated soil profile and in the water table aquifer to minimise computational and data requirements. In this paper, the conceptual framework and the theoretical development of SWAGSIM are presented.

## 2. Theory

### *2.1. Water balance processes modelled by SWAGSIM*

The conceptual model of SWAGSIM is presented in Fig. 1. Details of the water balance processes are presented in subsequent sections.

### *2.2. Runoff*

The surface runoff that follows rain and/or irrigation events is treated as a fraction of the total water applied in SWAGSIM. The fraction is defined on the basis of physical attributes such as slope, soil water content, land cover, and rate of application, and non-physical attributes such as farmer practices and farm irrigation layout.

The runoff is estimated immediately after each application, and is not included in any further computations. SWAGSIM permits the user to assume that a percentage of rain or irrigation runs off every field following every application during the modelling period. However, if the true surface runoff component for each application of water to each field can be estimated, it can be subtracted from the applied water, and the runoff fraction set to zero.

### *2.3. Macropore recharge*

Water is assumed to enter the soil via cracks as macropore flow, and the soil matrix as micropore flow. Macropore ($K_{SM}$) and micropore ($K_S$) saturated hydraulic conductivities must therefore be defined.

Following application of water at the soil surface and estimation of runoff, an amount of water equivalent to the micropore hydraulic conductivity is allowed to enter the soil. Subsequently, water equivalent to the difference between the macropore (i.e. crack) hydraulic conductivity and the micropore hydraulic conductivity is allowed to enter the soil profile and recharge the water table. Although this water bypasses the root zone and subsoil during the execution of the groundwater flow module, it will cause the water table to rise and increase the soil water content. Any water which is in excess of these infiltrated amounts is retained at the soil surface and becomes part of the water balance for the next day.

The above logic will not be appropriate when the water table is deep and the cracks do not reach the water table. Under such circumstances, lower values of $K_{SM}$ must be used to compensate.

### *2.4. Modelling net flux of water entering or leaving the soil surface through micropores*

The rate at which water enters or leaves the soil surface, net flux ($q_O$), is the upper boundary condition for modelling water movement through interconnected micropores within the unsaturated zone. The following methodology is adopted for the determination of $q_O$.

*Step 1.* Determine daily potential evapotranspiration ($E_p$) from climatic variables. A modified Penman model is used for this purpose:

$$E_p = \frac{\left(\frac{\Delta}{\Delta + \gamma}\right)R_n + \left(\frac{\gamma}{\Delta + \gamma}\right)f(u)(e_0 - e)}{L} \quad (1)$$

where:

$R_n$: Net radiation (MJ $m^{-2}d^{-1}$)
$G$: Ground heat flux (MJ $m^{-2}d^{-1}$)
$\gamma$: Psychrometric constant (kPa °$C^{-1}$)
$u$: Wind speed (km $d^{-1}$)
$e_0$ Saturated vapour pressure (kPa)
$e$: Daily saturated vapour pressure at dew point (kPa)
$L_h$: Latent heat of vaporisation (MJ $kg^{-1}$).

The $\Delta$ term is calculated from Maas and Arkin (1978) as:

$$\Delta = 0.1\left[\exp\left(21.255 - \frac{5304}{T_m + 273.1}\right)\right]\left[\frac{5304}{(T_m + 273.1)^2}\right] \quad (2)$$

where $T_m$ (°C) is the mean daily dry bulb temperature, and is calculated by:

$$T_m = \frac{(T_{mx} + T_{mn})}{2} \quad (3)$$

where $T_{mx}$ is the maximum and $T_{mn}$ is the minimum daily temperature. The psychrometric constant ($\gamma$) is taken to be 0.066 kPa °$C^{-1}$.

The ground heat flux ($G$) is calculated as:

$$G = 0.12(T_m - T_{av}) \quad (4)$$

where $T_{av}$ is the mean temperature for the preceding three days (Jensen *et al.*, 1971).

The wind function for the Penman equation is defined by,

$$f(u) = 14.74 + 0.055u \quad (5)$$

The mean daily saturated vapour pressure ($e_0$) is calculated as (Kimball, 1981):

$$e_0 = 0.6108 \exp\left(\frac{17.27T_m}{T_m + 237.3}\right) \quad (6)$$

The daily saturated vapour pressure at dew point ($e$) is calculated as:

$$e = 0.6108 \exp\left(\frac{17.27T_{dew}}{T_{dew} + 237.3}\right) \quad (7)$$

where $T_{dew}$ is the daily dew point temperature (°C). The latent heat of vaporisation of water ($L_h$) is often

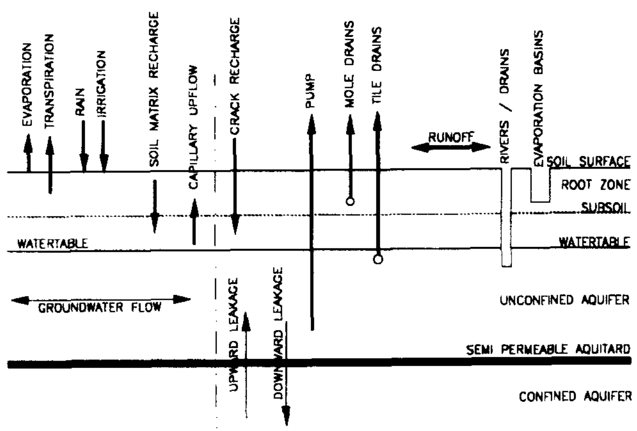


Fig. 1. Conceptual framework of SWAGSIM.

taken as a constant, but may be calculated as a function of $T_m$ (Fritschen and Gray, 1979), such that:

$$L = 2.50025 - 0.002365T_m \quad (8)$$

The daily net radiation ($R_n$) is estimated using (Meyer *et al.*, 1987):

$$R_n = -0.33 + 0.59R_s - G \quad (9)$$

where $R_s$ is the measured daily irradiance (MJ $m^{-2}$).

*Step 2.* Determine daily crop evaporation ($E_c$). This is obtained by multiplying the potential evapotranspiration by appropriate crop factors ($K_c$). The variation of $K_c$ during the growing period for several crops available within SWAGSIM are presented in Fig. 2. The crop factors may be modified if necessary, and new crops and associated crop factor profiles may be added when appropriate.

*Step 3.* Determine actual evaporation ($E_a$). The actual evaporation is set equal to the crop evaporation if the ratio of volumetric soil water content to the saturated volumetric soil water content of the root zone (i.e. effective saturation) is greater than 0.7. Otherwise,

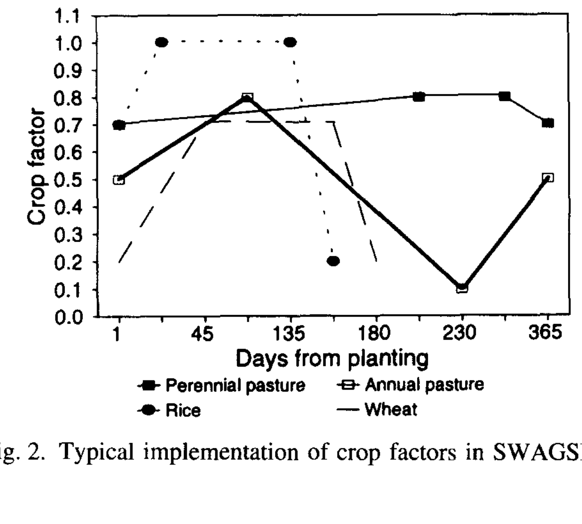


Fig. 2. Typical implementation of crop factors in SWAGSIM.

the actual evaporation is obtained by multiplying the crop evaporation by the effective saturation of the root zone. For situations when the water table is within the root zone, $E_a$ is set equal to $E_p$, and when the root zone water content reaches residual soil water content level, $E_a$ is set equal to the rate of capillary upflow from the water table.

*Step 4.* Determine flux to or from the unsaturated soil ($q_0$). The flux is obtained by subtracting the depth of rainfall and/or irrigation from the actual evaporation on a particular day.

### 2.5. Modelling soil water flow in the unsaturated zone

The objective of modelling the water balance components within the unsaturated zone is to determine vertical fluxes through soil matrix (recharge and capillary upflow) to and from the water table.

Under transient state conditions, the distribution of matric flux potential (Gardner, 1958; Raats and Gardner, 1974) within a homogeneous soil profile with roots above the water table is described by an infinite time series (Brandyk and Romanowicz, 1989). This solution was modified to estimate matric flux potential at the bottom of the root zone by Prathapar *et al.* (1992) using diffusivity and unsaturated hydraulic conductivity relations discussed by Philip (1987). The modified equation is defined by Eq. (10):

$$\Phi(Z,T) = Z\Phi_0/Z_0 + A(Z - Z_0) + \sum_{n=1}^{\infty} \{A_n \exp[-(1+\mu_n^2)T] + C_n\} w_n(Z) \qquad (10)$$

The dimensionless variables $Z$, $T$ and $Z_0$ are defined by Eqs (11a), (11b), and (11c), respectively:

$$Z = \frac{\alpha z}{2} \qquad (11a)$$

$$T = \frac{\alpha^2 tD}{4} \qquad (11b)$$

$$Z_0 = \frac{\alpha L}{2} \qquad (11c)$$

$$-\frac{\delta\Phi}{\delta z} - \alpha\Phi = q_0(t)z = 0 \qquad (12a)$$

$$\Phi = \Phi_0 \qquad z = L \qquad (12b)$$

$$\Phi = g(z) = -z \qquad t = 0 \qquad (12c)$$

For infiltration under a constant flux boundary condition and constant root water uptake [Eqs (12a)–(12c)], the parameters in Eq. (10) take the following form:

$$A = \frac{-\Phi_0/Z_0 - 2q_0/\alpha}{1 + 2Z_0} \qquad (13)$$

$$A_n = \frac{-8q_0\mu_n \sin\mu_n Z_0 + 16\mu_n S_r[2\sin\mu_n Z_0 + \mu_n \exp(-Z_0)]/\alpha(1+\mu_n^2)}{(2\mu_n Z_0 - \sin 2\mu_n Z_0)\alpha(1+\mu_n^2)} \qquad (14)$$

$$C_n = \frac{16\mu_n(q_0 - \Phi_0\alpha - S_{rx})[2\sin\mu_n Z_0 + \mu_n \exp(-Z_0)]}{(2\mu_n Z_0 - \sin 2\mu_n Z_0)(1 + 2Z_0)(1+\mu_n^2)^2\alpha} \qquad (15)$$

$$w_n(Z) = \exp(Z)\sin\mu_n(Z_0 - Z) \qquad (16)$$

$$S_{rx} = \frac{S_r}{\alpha(1 + 2Z_0)} \qquad (17)$$

$$\mu_n = -\tan\mu_n Z_0 \qquad (18)$$

$$\Phi = \int_{-\infty}^{\psi} K(\psi)d\psi = \frac{K(\psi)}{\alpha} \qquad (19)$$

$$\Phi_0 = \int_{-\infty}^{0} K(\psi)d\psi = \frac{K_s}{\alpha} \qquad (20)$$

$$\frac{dK}{d\theta} = \alpha D \qquad (21)$$

where

| | |
|---|---|
| $\theta$: | Volumetric soil water content of the root zone |
| $z$: | Vertical ordinate |
| $D$: | Soil moisture diffusivity |
| $K_s$: | Saturated hydraulic conductivity of micropores |
| $\psi$: | Matric potential |
| $K(\psi)$: | Unsaturated hydraulic conductivity |
| $\alpha$: | $K(\psi)$ versus $\psi$ soil parameter |
| $S_r$: | Rate of root water uptake |
| $L$: | Depth to water table |
| $t$: | Time |
| $q_0$: | Net flux |
| $n$: | Ranges from 1 to infinity |

To estimate capillary upflow, the soil profile was divided into an effective root zone and a subsoil. The minimum ($L_{min}$) and maximum ($L_{max}$) depth of effective root zone are set at 0.2 and 0.5 m within SWAGSIM. The actual depth of effective root zone for a non-rice crop on a particular day was determined as:

$$L_{rz} = \max[L_{min}, L_{min} + (K_c - 0.2)(L_{max} - L_{min})] \qquad (22)$$

For rice, the depth of effective root zone was based on a minimum root depth of 0.2 m on the day after rice water drainage, and a maximum depth of 0.4 m at harvest.

The daily capillary upflow from the watertable ($J$) was calculated using:

$$J = \frac{\Phi_0 - \Phi_{rz}}{L - L_{rz}} - K_{rz} \qquad (23)$$

where $\Phi_{rz}$ is the matric flux potential at the root zone, $L_{rz}$ is the effective depth of the root zone, and $K_{rz}$ is the unsaturated hydraulic conductivity at the bottom of the root zone.

The following conditions have been placed on the vertical fluxes calculated by SWAGSIM to maintain physical relevance:

- recharge through micropores cannot exceed the saturated hydraulic conductivity of the micropores, $K_{SM}$;
- capillary upflow rate cannot exceed net evaporative flux, $q_O$; and
- net evaporative flux ($q_O$) is equal to the potential evapotranspiration rate ($E_p$) when the water table is within the root zone.

### 2.6. Determining unsaturated hydraulic conductivity

Estimation of the matric flux potential requires the unsaturated hydraulic conductivity of the soil at the bottom of the root zone ($K_{rz}$). This parameter is estimated by Gardner (1985):

$$K_{rz} = K_s \exp(-\alpha\psi) \tag{24}$$

where $K_S$ is the saturated hydraulic conductivity of the soil, $\psi$ is the matric potential and $\alpha$ is the soil parameter. SWAGSIM provides an estimate of $\alpha$ for each soil type based on the saturated hydraulic conductivity of micropores. It is derived from the assumption that the difference in unsaturated hydraulic conductivities between soil types is negligible at a matric potential of 250 m, and is equal to exp(−2000) m d$^{-1}$. If this assumption is unacceptable for the soil types to be modelled, an experimentally determined or calibrated value of $\alpha$ can be used.

### 2.7. Interaction between supply/drainage channels and the unconfined aquifer

The modelling of the interaction of irrigation supply and drainage channels and the unconfined aquifer is adapted from the river package used by the MODFLOW groundwater model (McDonald and Harbaugh, 1984). The streambed conductance ($C_{riv}$) is estimated using the length ($L_{riv}$) and width ($W_{riv}$) of the channel(s) in a given finite difference cell, the thickness of the riverbed sediments ($M_{riv}$), and their vertical hydraulic conductivity ($K_{riv}$), as described by Eq. (25).

$$C_{riv} = \frac{K_{riv}L_{riv}W_{riv}}{K_{riv}} \tag{25}$$

The rate of recharge or discharge between the channel and the aquifer ($Qr_{i,j}$) is calculated from:

$$Qr_{i,j} = -C_{riv}(h_{riv} - h_{i,j}) \quad h_{i,j} > z_{RB} \tag{26a}$$

$$Qr_{i,j} = -C_{riv}(h_{riv} - z_{RB}) \quad h_{i,j} \leq z_{RB} \tag{26b}$$

where $h_{riv}$ is the head in the channel and $z_{RB}$ is the elevation of the bottom of the streambed. The negative sign represents recharge to the unconfined aquifer.

If a cell contains rivers and channels, then a weighted value for each variable representing the combination of river and channels should be used.

### 2.8. Leakage between unconfined and confined aquifers

The leakage of water between the unconfined aquifer and the underlying confined aquifer is determined by:

$$Ql_{i,j} = K'(h^u_{i,j} - h^c_{i,j}) \tag{27}$$

where $K'$ is the leakance between the aquifers, $h^u_{ij}$ is the water table elevation in the unconfined aquifer and $h^c_{ij}$ is the piezometric level in the confined aquifer. Therefore, when $h^u_{ij}$ is greater than $h^c_{ij}$ leakage to the confined aquifer will occur, otherwise upward, leakage will occur.

### 2.9. Groundwater pumping

Pumping from the unconfined aquifer is considered as a sink in the groundwater flow equation. The pumping rate (m d$^{-1}$) is estimated from the total volume pumped, the area of the finite difference cell in which the pump is located, and the duration of pumping.

### 2.10. Mole drains

Mole drains are treated as sinks in the groundwater flow equation. The volume of water drained ($V_{mole}$) is determined from the specific yield ($S_{ij}$), the area mole drained within a finite difference cell ($A_{mole}$), depth of mole drains beneath the soil surface ($z_{mole}$) and the depth to water table ($z$), as described in Eq. (28). The mole drainage rate ($Qm_{ij}$) for the entire cell is then estimated from the drainage volume and cell area ($A_{ij}$).

$$V_{mole} = S_{i,j}\,(z_{mole} - z)A_{mole} \tag{28}$$

$$Qm_{i,j} = \frac{V_{mole}}{A_{i,j}} \tag{29}$$

Drainage only occurs if the water table rises above the elevation of the mole drains.

### 2.11. Tile drains

Drainage through tile drains is treated as either discharge through pumps or mole drains. For conditions when the tiles are always at or below the elevation of the shallow water table, the drains may be treated as groundwater pumps. A lower pumping rate is then used to simulate the effects of tile drainage. The drainage rate is estimated from the total volume drained, area of the finite difference cell where drains are located, and the duration for which the tile pump was run.

If tiles are at or below the water table only for a part of the season (modelled period), then the mole drain option can be used to simulate the effects of tile drainage.

### 2.12. Evaporation basins

Evaporation basins are considered as sources to the unconfined aquifer. Initially, recharge volume is calculated from area of the evaporation basin, duration of ponding and leakage rate. Subsequently, the recharge rate is estimated from recharge volume and area of the finite difference cell.

### 2.13. Modelling groundwater flow in the unconfined aquifer

The objective of modelling the groundwater flow is to determine the spatial response of the water table aquifer to changes in vertical fluxes influenced by the hydraulic properties of the aquifer and the piezometric gradients. This is achieved by solving the partial differential equation governing the non-steady-state, two-dimensional flow of groundwater in an unconfined, non-homogeneous, and isotropic aquifer assuming that the change in transmissivity due to changes in the thickness of the saturated zone is negligible (Prickett and Lonnquist, 1971). The iterative alternating direction implicit (IADI) procedure based on a finite difference approach is used in SWAGSIM to solve the groundwater flow equation (Eq. (30)).

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + Q \qquad (30)$$

where

| | |
|---|---|
| $T$: | Aquifer transmissivity |
| $h$: | Piezometric head in unconfined aquifer |
| $t$: | Time |
| $S$: | Specific yield |
| $Q$: | Net recharge |
| $x,y$: | Cartesian coordinates. |

### 2.14. Boundary conditions for groundwater flow

Constant head, no flow, time-varying head and time varying flux boundary conditions are allowed within SWAGSIM. For the finite difference cells (FDCs) where a constant head boundary condition is specified, SWAGSIM assigns a head-specific yield value. Zero transmissivities are assigned to those FDCs for which no-flow conditions are required.

For those FDCs requiring time-varying heads, SWAGSIM allocates high specific yield values, and resets the appropriate piezometric levels of the unconfined aquifer at specified time intervals. Time-varying flux conditions are simulated by resetting the flux rates at specified time intervals.

### 2.15. Lateral groundwater flow in the deeper aquifer

SWAGSIM does not model changes in piezometric levels in the deeper confined aquifer. Initial piezometric level are assumed to remain steady during the modelling period. If this approximation is inadequate, sensitivity analysis for the expected range of piezometric levels can be conducted.

## 3. Spatial and temporal discretisation

SWAGSIM utilises two different grids to minimise computational and data requirements. The first grid represents homogeneous land-use units (e.g. fields, paddocks, irrigation bays) within the irrigation area (see Fig. 3). The land-use units are used to determine recharge or discharge through the soil surface on a particular day. SWAGSIM assumes that a unit has a single land use, with rain and irrigation applied uniformly within this unit. Therefore, it is recommended that for the purpose of representing the farms, they are subdivided into smaller units to reflect homogeneous land-use and irrigation practices.

The second grid is used to estimate other vertical flux components (i.e. recharge, groundwater pumping, tile and mole drainage, river recharge, leakage) and to solve the finite difference approximation of the groundwater flow equation (Fig. 4). SWAGSIM incorporates variable grid sizings within the finite difference mesh. The structure of SWAGSIM allows for cell dimensions of $X$ m and $0.5X$ m in width, and $X$ m and

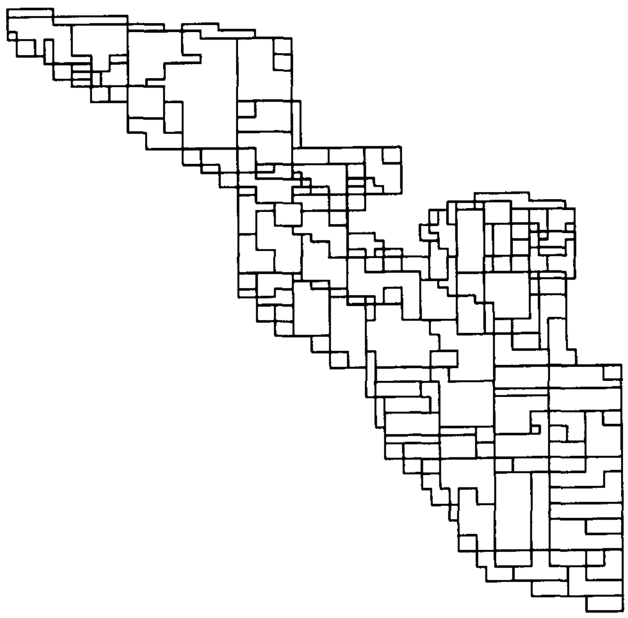

Fig. 3. Representation of fields in SWAGSIM.

0.5*X* in length. The finite difference cell dimensions are therefore restricted to $X \times X$, $X \times 0.5X$, $0.5X \times 0.5X$, and $0.5X \times X$.

The following must be taken into consideration when designing the finite difference grid:

(1) At least one FDC must be assigned to every land-use unit. Therefore, the area of the smallest finite difference cell must be less than or equal to the smallest land-use unit within the study area. This will permit evaluation of management practices in every land-use unit.
(2) The boundary of a group of adjacent finite difference cells should approximate the boundary of the land-use unit superimposed (see Fig. 4).
(3) The boundary of a group of finite difference cells should approximate the boundary of the irrigation area modelled (see Fig. 4).
(4) Irrigation and land-use data of adequate quality must be available for each land-use unit.
(5) The number of land-use units and the finite difference units must be kept to a minimum to minimise computing.

The minimum time step allowed in SWAGSIM is a day for saturated and unsaturated flow modules. For areas where water table fluctuation is rapid, a daily time step for both modules is recommended. A longer time step is allowed for the groundwater module if necessary.

## 4. Software structure

SWAGSIM is optimised for the Microsoft Windows operating system. Input data is imported using a pre-processor (written in Microsoft VisualBasic), checked for quality and accuracy, and stored in a Microsoft Access database file. The simulation model is written in Microsoft C++, with model output being written to a Microsoft Access database. Users will require Microsoft Windows 3.1 or later, and Microsoft Access Version 2.0 to run SWAGSIM.

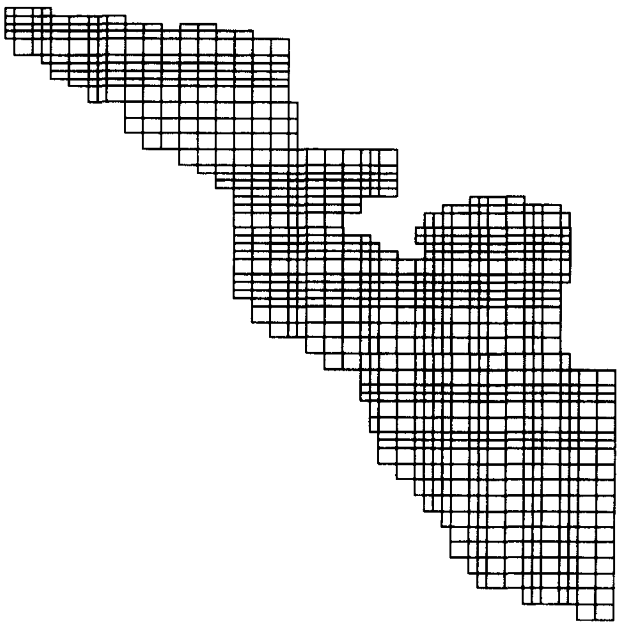

Fig. 4. Finite difference representation in SWAGSIM.

## 5. SWAGSIM applications to date

SWAGSIM has been successfully used to determine the impact of rice-growing in the Murrumbidgee Irrigation Area (MIA) of New South Wales (Prathapar *et al.*, 1994a), to evaluate the feasibility of using shallow groundwater pumps to control water tables in the MIA (Prathapar *et al.*, 1994b), to evaluate subsurface drainage options for the Mead Ridge project area in Victoria, (Prathapar *et al.*, 1995; Poulton, 1996), and to evaluate groundwater discharge into the Hunter River of New South Wales (Punthakey and Prathapar, 1995).

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