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Evaluation and application of DRAINMOD in an Australian sugarcane field

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ABSTRACT

DRAINMOD is a water management model developed to simulate the performance of drainage and water table control systems for shallow water table soils, and it has been widely used in the United States over the last 20 years. This model has been evaluated and applied for predicting water table fluctuations in a sugarcane field for acid drainage management in north-eastern New South Wales, Australia. The reliability of the model has been evaluated using 2-year experimental field data from water level recorders installed in a sugarcane field. Good agreement was found between the observed and simulated values with a standard error of about 0.07 m. However, the model is not readily applicable to daily water management in Australian soils since it requires extensive soil and climate data, which are normally not available for most Australian sugarcane areas. In this application, refinements have been attempted in evapotranspiration estimation and in soil input data preparation so that the model requires only easily obtainable input data but still retains acceptable accuracy. With these improvements, the model can be used as a practical tool for investigating drainage management options for different site conditions. This will assist decision-makers in providing appropriate subsurface drainage management policies, such as acid drainage management, in Australian estuarine sugarcane areas.

1. Introduction

In the last 15 years, massive fish kills and fish diseases have been reported in some Australian estuaries, particularly where sugarcane (*Saccharum* spp.) is the main cropping (White et al., 1993). Investigation shows that such phenomena are related to the contamination of estuaries by toxic drainage water from acidic soils found in Australian coastal floodplains (White et al., 1993; Wilson et al., 1999). It is apparent that the existing water management strategy in this area is responsible for observed fisheries problems and will run greater risk in the future with prolonged drought episodes if no appropriate measures are taken. Furthermore, population growth and increasing demand of land along coastal areas in Australia are making this problem gradually more serious. Conflicts between land users and land managers continue to arise.

In Australia, sugarcane is mainly grown along the north-eastern tropical and subtropical coastlines and shallow water tables are a common feature of this region, as well as in many sugarcane growing regions in the world (Hurst et al., 2004). The position and dynamics of the water table play an important role in the growth of sugarcane and the export of acidity in areas of acid sulfate soils (ASS). Studies show that sugarcane yields have a favourable response to water management (Carter et al., 1988; Hurst et al., 2004). Operation of the AUSCANE model (Russell, 1990) in Australian cane lands has also confirmed that sugarcane yields are very sensitive to high-water tables with substantial reductions in yield occurring when water tables are close to the soil surface (or above

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the root zones) for lengthy periods (i.e. a few weeks). In the study area of north-eastern New South Wales (NSW), sugarcane growers believe that yields are greater when soils are well drained. However, the drainage systems, designed to increase cane production, may cause environmental problems such as acid drainage outflows and, consequently, fish kills where sugarcane grows on ASS (White et al., 1993; Wilson et al., 1999). It is clear that predicting water table fluctuations in response to the various hydrological factors will provide very useful information on water management for sugarcane growth and acid drainage control (Wilson et al., 1999).

DRAINMOD (Skaggs, 1980a,b) predicts, on a day-by-day basis, the water table position, soil water content, drainage, evapotranspiration and surface runoff for given climate data, soil and crop properties, and water management system design parameters. The model is based on a water balance in the soil profile and composed of a number of separate components. The model, widely used over the United States and gradually being adopted by other countries in the last 15 years, provides good results for most applications (Skaggs, 1982; Fouss et al., 1986, 1987; Sabbagh et al., 1993; Borin et al., 2000; Sands et al., 2003; Skaggs et al., 2005). The model has been successfully tested and applied in a wide variety of geographical locations and soil conditions, such as in Jordan (Sinai and Jain, 2006), and adequate application references are available on the DRAINMOD web site (http://www.bae.ncsu.edu/soil_water/drainmod/dm_papers.htm). Recently, the capability of the model has been extended to predict the effects of drainage and water management practices on the hydrology and water quality of agricultural and forested lands both on field- and watershed-scale. However, applications of this model were rare in Australian soils (Cox et al., 2004), especially in the north-eastern NSW floodplain agricultural area which has similar climate conditions to that where the model was originally developed (Yang et al., 2000b). The purpose of this study was to test the reliability of DRAINMOD (the basic hydrologic module) for water table prediction in an Australian floodplain agricultural environment, and to apply the model to assist in the prediction of acid outflow events from the sugarcane fields that may cause environmental degradation. Refinements have also been attempted to make the model more easily applicable to Australian sugarcane fields. In the future, the improved DRAINMOD and its new extensions are to be further assessed and applied in other areas to assist in water management.

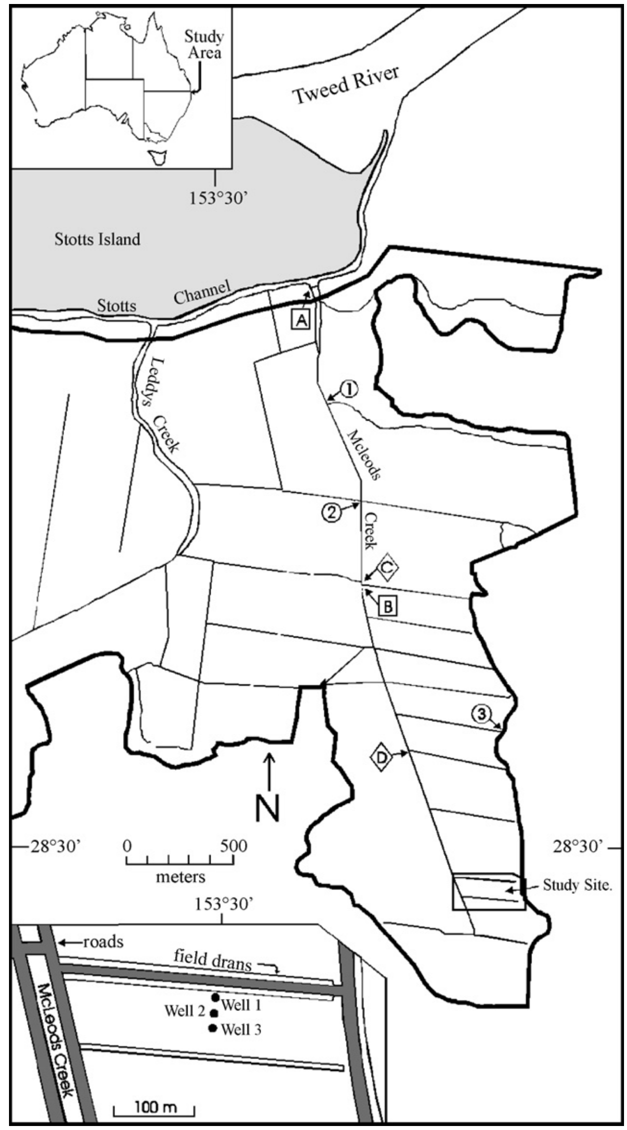

Fig. 1 – The McLeods Creek study site showing the position of one-way flood gates (□), pump stations (○), drains (—), water quality data loggers (◇) and the boundary of the sugar cane (▬, bold line). Detail of the measurement sites is shown in the bottom left-hand corner inset.

2. Study site

The site selected for this study was a sugarcane field on the estuarine floodplain at McLeods Creek, a tributary of the Tweed River, on the far north coast of NSW, Australia. The whole catchment area is about 4.5 km^2 centred at 28°18′S and 153°31′E. The dimensions of the catchment is approximately 3.0 km × 1.5 km with the longer axis of catchment running north–south (Fig. 1). The Tweed River drains a catchment of approximately 1000 km^2 bounded by mountain ranges to the west. The climate is humid and subtropical with average annual rainfall greater than 1400 mm: a pronounced wet season extends from December to March, cyclonic activity is common and very high rainfalls of short duration have been recorded; summers are warm to hot, and winters are warm and dry, and moisture deficits on the north coast of NSW are common in spring and early summer (Wilson et al., 1999).

The whole floodplain catchment of McLeods Creek is used for sugarcane farming, which has become the dominant land use since the 1960s. The sugarcane crop cycle in Australia is dependent on the climate: a 1-year crop cycle is possible if conditions are favourable, whereas, in less favourable conditions a 2-year cycle is required. The sugarcane grown in northern NSW is at the southern extremity of what is usually considered a 1-year growing season. Due to the long history of sugarcane farming and the improvement of drainage techniques, the study area has a complicated and intensive drainage network system with a drain density of 21.6 km/km^2 and over 100 km of canals. McLeods Creek itself is the largest drain and has been widened and straightened and is periodically dredged to ensure free drainage. Mole drains, about 0.3 m below the soil surface at 3–5 m spacing, drain directly into the field drains. The field drains (the smallest surface drains) surround each cane block and are designed to directly drain the soil under the growing sugarcane; they are usually excavated to a depth of 0.5 m and are periodically cleaned. They either drain directly into McLeods Creek or flow into larger lateral drains that collect water from several field drains and then discharge into McLeods Creek. One-way flood gates at the junction of McLeods Creek and Stotts Channel (Gate A, see Fig. 1) and at 1.35 km upstream (Gate B) were installed to stop the influx of tidal water during high tide. They are designed to open at low tide and allow outflow of flood water after rainfall. Pumping to rapidly reduce high-water tables after rainfall is carried out at three points marked with 1, 2 and 3 (Fig. 1).

An experimental station was established in 1991 on a small sugarcane block (approximately 2 ha). Three piezometers, at Wells 1, 2, and 3 (Fig. 1), monitored the position of the water table at 5 min intervals for about 2 years between 2 February 1992 and 29 January 1994. The level of all three piezometers was surveyed with an automatic level and recorded relative to the Australian height datum (AHD). Recording the position of the water table in each piezometer was carried out with a shaft encoder water level instrument (Unidata Model No. 6509b). A weather station at Well 2 had a combined plastic-film capacitance humidity sensor and platinum resistor temperature probe, anemometer, tipping bucket rain gauge and a radiation balance transmitter with lupolene domes. The recorded weather data include the ambient temperature, humidity, net radiation, rainfall and wind speed. All data were logged on site and downloaded weekly via a mobile telephone and modem. In the past 10 years, a large number of scientific studies have been carried at this site on acid sulfate soils and hydrology (White et al., 1993; Wilson et al., 1999; Yang et al., 2000a,b). Those relevant studies provided useful data sets and information for the model development and validation in this study.

3. Evaluation of DRAINMOD

3.1. Model description

Detailed description and examples of DRAINMOD can be found in Skaggs (1980a,b) and a great amount of other literature. Briefly, the basic hydrologic module is based on the water balance of a thin section of soil of unit surface area which extends upward from an impermeable layer to the surface, whilst the model point is located midway between adjacent drains. The water balance for a unit surface area at a time increment (Δt) may be expressed as

$$\Delta V_a = D + ET + DS - F \quad (1)$$

where ΔV_a is the change in the water-free pore space or air volume (mm), D the drainage from or sub-irrigation into the section (mm), ET the evapotranspiration (mm), DS the deep seepage (mm), and F is infiltration (mm) entering the section in a time increment Δt.

Infiltration, F, is predicted by a modified Green-Ampt equation: $f = A/F + B$. A (mm^2/h) and B (mm/h) are parameters that depend on soil and plant properties, and rainfall. The model requires a table of A and B versus water table depth (WTD). The lateral flux is evaluated in terms of the water table elevation midway between the drains and the water level or hydraulic head in the drains. DRAINMOD employs the Hooghoudt steady-state equation for the lateral flux, as used by Bouwer and van Schilfgaarde (1963). The determination of evapotranspiration (ET) is a two-step process. First, the daily potential evapotranspiration (PET) is calculated by the Thornthwaite method which requires only daily maximum and minimum temperature and geographic location as input information (Skaggs, 1980a). After PET is calculated, the model determines whether ET is limited by soil water conditions.

3.2. Model input data

The primary input data required to run the DRAINMOD hydrologic model include weather data, soil data, crop data and drainage system parameters. The weather data needed to run DRAINMOD are hourly rainfall, and daily maximum and minimum temperature. The hourly and daily values were calculated from the weather data-logger measurements (at 5 min interval) for 1992 and 1993. Any missing data were predicted from nearby meteorological stations by using regression analyses. A computer program has been developed to extract these data and convert them to the format readable by DRAINMOD for estimation of evapotranspiration.

The soil at the experimental site is identified as an acid sulfate soil (White et al., 1993) and can be divided into three natural horizons: (1) organic-rich surface layer (0–0.3 m), (2) very acidic jarosite layer (0.3–0.9 m) and (3) pyrite layer (impermeable estuarine clay, below 0.9 m). Table 1 shows the characteristics of each soil layer in the study site.

The soil related input tables required by DRAINMOD contain the following information: relationship of water table depth to drained pore volume, Green-Ampt parameters and the water upward flux to the root zone, soil water characteristic curve (SWCC), saturated hydraulic conductivity and water content at wilting point. The SWCC is a basic soil property and several parameters needed to run DRAINMOD can be derived from it (Skaggs, 1980b). In this study, SWCC was determined in the laboratory using the ‘High Energy’ method (Klute, 1986).

Table 1 – The characteristics for different soil horizons at the study site

	Soil layer		
	1	2	3
Depth (m)	0.0–0.3	0.3–0.9	>0.9
Bulk density (t/m^3)	1.05	0.95	0.70
Saturated hydraulic conductivity (mm/h)	33.0	28.6	1.1
Porosity (m^3/m^3)	0.60	0.63	0.73
Solid (%)	40	37	27
Water (%)	52	57	67

The relationship between drainage volume and water table depth was used in the model to determine how far the water table falls or rises when a given amount of water is removed or added. From Skaggs (1980b), the slope of the plot of drainage volume (V_a) versus water table depth is the drainable porosity (p). Therefore, if p is known or can be approximated for each soil horizon, drainage volume (V_a) can be estimated as

$$V_a = p_1 \times \text{WTD} \quad \text{when} \quad \text{WTD} < 300\,\text{mm} \tag{2}$$

$$V_a = p_2 \times \text{WTD} \quad \text{when} \quad \text{WTD} > 300\,\text{mm} \tag{3}$$

where V_a is the drainage volume (mm), p_1 and p_2 are the drainable porosities of layers 1 and 2 determined by the SWCC laboratory method (Klute, 1986), and WTD is the water table depth from the surface (mm). With the soil characteristics shown in Table 1, the V_a–WTD relationship can be calculated and presented as a table in the DRAINMOD input format.

The Green-Ampt infiltration parameters (A and B) were determined by $A = K_s M S_{av}$ and $B = K_s$, where K_s is the vertical hydraulic conductivity (mm/h), M the fillable porosity (water content as saturation in m^3/m^3 minus the water content at the desired water table depth), and S_{av} is the effective suction at the wetting front (mm). The values for A and B were determined as a function of water table depth and presented in a table as input.

The effective root depth was assumed to be time dependent, and was estimated to be 0.45 m when the crop was at the peak of its growth (Julian day 55–110). Soil water from a shallow surface layer will be removed by evaporation even if the land is fallow. Therefore, an effective root zone depth of 0.03 m was assumed for fallow periods when no crop was growing (around Julian day 273). The time-dependent effective root depth used in the model was adapted and modified from Gayle et al. (1990).

Most of the input data for drainage system parameters were directly measured in the field and are listed in Table 2. These data were used in combination with the soil data to compute surface runoff, drainage flow, sub-irrigation, evapotranspiration and water table depth in the simulation process.

3.3. *Model evaluation*

The piezometer at Well 3 was located in the middle of the monitored cane block and the measured water height data were used to compare with the simulation results of WTD fluctuation for the years of 1992 and 1993 (Fig. 2).

Table 2 – Drainage system parameters in the study site

Parameter	Value
Drain depth	0.70 m
Effective depth from drain to impermeable layer	0.50 m
Distance between drains	100 m
Actual depth from drain to impermeable layer	1.20 m
Surface storage that must be filled before water can move to drain	5.0 mm
Width of ditch bottom	0.7 m
Side slope of ditch (horizontal:vertical)	0.20:1.00
Initial water table depth	0.0 m

The comparison shows that the DRAINMOD predicted water table fluctuations are generally in good agreement with that measured in the field, with a standard error of about 0.07 m by regression analysis. The best agreement occurred for water tables above rooting depth (about 0.5 m from the soil surface) in relatively wet seasons. For example, the water table was high during a large part of the first half of 1992, reflecting the high rainfall of this subtropical wet season. Large errors mostly occurred in relatively dry periods (such as early and late 1993) when the water table reached the lowest position (about 1.5 m below the surface). Human activities and water table management practices might also contributed to prediction errors. For example, the large errors around November 2003 might be associated with the cane harvesting in that block, and the ET model was not readjusted properly.

Inspection of the results shows that the simulation in the relatively dry periods, such as in the early part of 1993, has the worst agreement, under-predicting the degree of fall in the WTD (about 0.7 m). It is during this period that DRAINMOD under-predicted ET as compared to a Resistance Energy Balance Model (REBM), namely RADCALC (Jupp, 1992). In DRAINMOD, ET is estimated based on an empirical relationship between potential ET and mean air temperature (known as the Thornthwaite method). The disadvantages and deficiency are widely recognised and it is recommended that a better ET model be used if available (DRAINMOD User Manual). It was believed that improvement on ET estimation might result in better water table prediction. For such consideration, we simply replaced the ET module with the REBM model (RADCALC) to prepare the ET input data for DRAINMOD. After this replacement, while the other inputs remained the same, the simulation results were significantly improved and the standard error reduced to about 0.06 m.

Comparison of the measured and predicted water tables also reveals that the model is in good agreement only when the water tables are within a certain range, but it failed to predict extreme conditions. In some cases (e.g. in early and mid-1993) the rise of the water table in the observation well is faster and higher than the rise predicted by the model. One of the explanations is that an observation well serves as a sink for infiltrated rainfall and causes a temporary rise of the water level due to soil cracks which were seen around the well. It was believed that readjustment of drainage volume and water table depth might help to solve this problem (Skaggs, personal communications, 1995).

DRAINMOD requires a lot of soil input data in specific format (.SIN), and some of them (such as SWCC and hydraulic conductivity) are not easily obtainable in most Australian sugarcane areas. There is a need to develop easier means for soil input data preparation to increase the model applicability.

4. Application of DRAINMOD with refinements

Based on the above evaluation, the attempted refinements on DRAINMOD application were related to ET estimation and soil input data preparation. To achieve these refinements, additional computer programs were developed to prepare the DRAINMOD input tables using only the easily obtainable soil

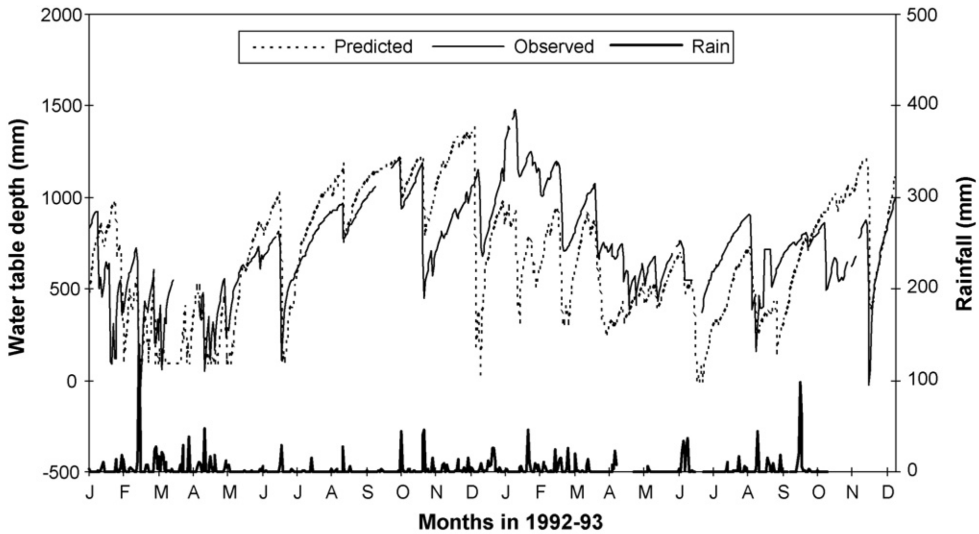

Fig. 2 – Observed and predicted water table depth using DRAINMOD.

and weather data whilst still retaining acceptable accuracy. The procedures are illustrated in Fig. 3.

The basic input data necessary to run the RADCALC energy balance module (PRERAD) are the daily maximum and minimum temperatures and daily rainfall. The data can be obtained from any meteorological station in Australia. In this study, however, these data were derived from the raw data recorded by the data logger at our McLeods Creek study site and converted to the required input format with the location information (latitude, longitude and elevation). Any missing data were derived by regression from the Condong Sugar Mill data (the nearest meteorological station). A computer program (LOG2RAD) was developed to prepare the input file for RADCALC (.BAS) from the data-logger records. Then, the output file (.PSF) from RADCALC energy balance module (PRERAD) was converted to the DRAINMOD potential ET input file (.PET) using another computer program (RAD2DM). These programs are used jointly to create the input tables with programs for the soil parameter estimates.

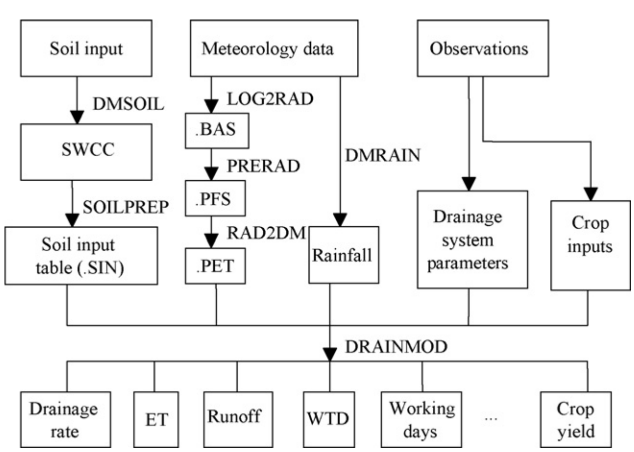

Fig. 3 – Procedures of DRAINMOD application with refinements.

The hydraulic conductivity and SWCC should be measured whenever possible. However, it is time and labour consuming to make these field and laboratory measurements. In this case, they may be predicted from more easily obtainable data (Williams et al., 1992). A simple method developed by Jabro (1992) was adopted to predict the saturated hydraulic conductivity of soils from their particle size distribution (silt and clay %) and bulk density (BD) data. The empirical relationship is

$$\log(K_s) = 2.7789 - 0.81\log(\text{silt }\%) - 1.09\log(\text{clay }\%) - 4.64(\text{BD}) \quad (4)$$

The SWCC can also be estimated from surrogate soil properties for which data are more easily available. The soil properties most often identified with the estimation of SWCC are soil texture, organic matter, and bulk density. The method introduced by Baumer and Rice (1988) is used in this study to model the SWCC and to prepare the soil input data. SWCC was estimated by

$$\text{WC} = \text{WCR} + \frac{\text{WCS} - \text{WCR}}{(1 + (\alpha h)^n)^m} \quad (5)$$

where WC is the water content (%) at a given suction h, WCR the residual water content (%), WCS the saturated water content (%) which can be estimated from BD and particle density, h the soil water suction or pressure head (m), and α, m, n are the equation parameters which can be determined from soil texture, organic content and BD.

Based on the above method, a computer program (DMSOIL) has been developed to predict SWCC from the easily obtained soil data (Table 1). These SWCC data were used as an input table to run the SOILPREP program that prepares soil input tables for DRAINMOD. These input tables are: SWCC table (Table 3), drainable pore volume–water table depth relationship and water table depth–upward flux relationship table (Table 4), and Green-Ampt parameter

Table 3 – Predicted soil water content (θ) at various pressure (or suction) heads

Pressure head (m)	θ (m^3/m^3)		
	Layer 1	Layer 2	Layer 3
0.0	0.305	0.400	0.550
−0.3	0.247	0.327	0.479
−0.5	0.229	0.309	0.462
−1.0	0.203	0.281	0.437
−1.5	0.190	0.266	0.422
−2.0	0.180	0.256	0.412
−3.3	0.165	0.239	0.395
−5.0	0.154	0.226	0.381
−10.0	0.136	0.205	0.360
−15.0	0.127	0.194	0.348
−50.0	0.103	0.165	0.315
−150.0	0.09	0.142	0.287

Table 4 – Predicted volume drained and upward flux relationships with water table depth

WT depth (m)	Volume drained (mm)	Upward flux (mm/h)
0.0	0.000	2.000
0.1	0.088	2.000
0.2	0.352	2.000
0.3	0.792	0.750
0.4	1.442	0.250
0.5	2.335	0.150
0.6	3.408	0.100
0.7	4.774	0.075
0.8	6.610	0.050
0.9	8.607	0.040
1.0	10.390	0.030
1.2	13.063	0.020
1.5	13.954	0.010
2.0	17.974	0.002

table (Table 5). These tables were finally combined to one soil input table (.SIN) which was then directly read by DRAINMOD for the simulation of drainage flow and water table depth.

Table 5 – Predicted Green-Ampt parameters from the soil water characteristic curve and hydraulic conductivity

Initial water table depth (m)	A (mm^2/h)	B (mm/h)
0.0	0.0	0.0
0.1	106.8	30.0
0.2	138.8	30.0
0.4	321.0	24.0
0.6	349.6	24.6
0.8	374.0	24.9
1.0	408.6	14.1
1.5	403.8	12.8
2.0	429.8	13.6

5. Results and discussion

Fig. 4 presents the simulated water table depth using the RADCALC ET model and the predicted soil inputs (Model 1). It is in good agreement with that using the measured soil input (DRAINMOD) and the observed water table depth (Observed). The water table fluctuation curve from the refined model followed the same pattern as that shown in Fig. 2. The predictions were better during the wet periods, but there were noticeable improvements in the dry periods (e.g. late 1992 and early 1993) compared with the previous results shown in Fig. 2. The overall standard error between the observed and the predicted WTD was slightly less than 0.07 m for the 2-year period (1992–1993). This seems satisfactory for a long period of water table simulation and suggests that the predicted soil input may be used in the absence of observed data as input to DRAINMOD to achieve acceptable simulation accuracy. Such accuracy might be largely due to the improved estimation of ET, the use of predicted soil input does not necessarily contribute to the increased accuracy, but it enhances the adoptability of the model.

This study had no intention to comprehensively evaluate or develop a water management model, but readjust the existing model to meet the specific needs for an Australian sugarcane field. All the limitations (Skaggs, 1980a) of the original model itself still exist. Most refinements were made to enhance the applicability of the model and to suit the objective

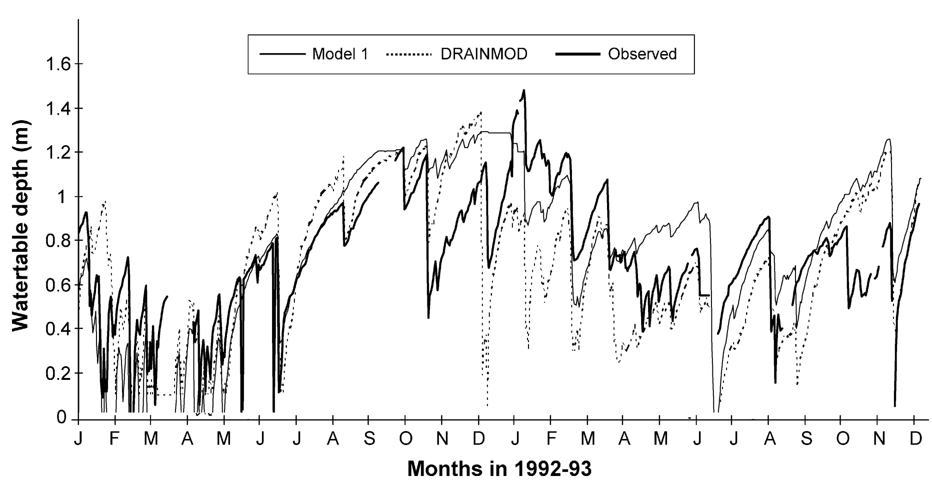

Fig. 4 – Comparison of water table simulation results using Model 1 (with refinements) and DRAINMOD with the observed water tables.

of the study which required long-time-series data on water table positions and drainage flow rates. These refinements were based on several assumptions to predict the model inputs and to simplify the modelling process. However, for any application of DRAINMOD, the measured data (particularly K_s and SWCC) should be used whenever possible. The methods introduced in this study should be used only as an alternative when the measured data are not available.

There were complete and continuous records of climate data for only 2 years (1992 and 1993), along with field measurements of soil properties, and they were used in the model evaluation and comparison. However, longer periods of measurement data should be used for the model assessment when available in the future.

Several case studies and applications using DRAINMOD predicted water tables have been presented in relevant papers (Wilson et al., 1999; Yang et al., 2000b). It has been proven that the predicted water tables can be successfully used in predicting acid outflow events. For example, the predicted water tables have been used in combination with hydrological modelling in a geographic information system to provide information for the typical questions in acid drainage control: (1) Does an outflow event happen with a rainfall event? (2) How much pollutant will this rainfall event bring into the estuary river system? (3) What happens to an individual cane block with each rainfall event? These case studies simulate the acid outflow for the whole catchment, as well as for each cane block, and predict the amount of acidic pollutant brought to the outlet for any individual rainfall event. In addition, these applications perform the continuous simulation of acid outflows at a detailed level for each cane block and each rainfall event. They provide acid outflow information in both spatial and temporal context, thus useful for detailed acid drainage control and management (Yang et al., 2000b).

6. Conclusions and further studies

In this study, a water management model (DRAINMOD) was evaluated for its performance in simulating drainage and water table for a sugarcane field in Australia. The evaluation shows that DRAINMOD can simulate the water table position fairly accurately in the shallow water table environment of Australian costal sugarcane areas. Refinements have been achieved by improving ET estimation and soil data input prediction. Methods have been developed to predict parameters needed to run DRAINMOD using only easily obtainable climate and soil data, but with retained acceptable accuracy of the model. With these refinements, DRAINMOD could become part of a practical tool for water table management in the sugarcane area in north-eastern NSW.

Further evaluation is needed if this model is to be applied elsewhere. Adjustments need to be made to soil-related coefficients, particularly the drainage volume and water table depth relationship, depending on soil and water conditions. Recently, DRAINMOD has changed and advanced significantly, and the model has gone from a strictly field-scale hydrologic model, to a water quality and watershed-scale model as well. The advances of the model and its interface and extensions (such as DRAINMOD-N, DRAINMOD-S) will make it more useful in land and water management. It is possible that this model and its extensions, when fully evaluated, being incorporated in the existing decision-support tools (such as TOOLS2) for routine monitoring and evaluation of land and water management.

With the development in REBM based ET estimation (SEBAL, Bastiaanssen et al., 1998; METRIC, Tasumi and Allen, 2007), it is possibility not only to improve the ET estimation but also to use remotely sensed data to predict ET across an area as diverse as that of the McLeods Creek sub-catchment when the drainage behaviour of the sub-catchment is to be considered (Yang et al., 1997, 2007). Integration of remote sensing and GIS with the model for input data preparation (e.g. drainage parameters and vegetation index extraction) and spatial analysis, will significantly improve the model efficiency and applicability.

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