An integrated drainage network analysis system for agricultural drainage management. Part 1: the system

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Abstract

This is the first of two papers that elaborate an integrated drainage network analysis system (IDNAS) for agricultural drainage management. In this paper, the system components, functions and implementation are presented. The IDNAS comprises an agricultural drainage network module, an evapotranspiration (ET) module and an event-based spatio-temporal module. The network module is designed to model a typical agricultural drainage system and to perform the specific tasks for network assessment, monitoring and simulation in a geographical information system (GIS). The ET module is used to estimate real-time evapotranspiration from remotely sensed imagery and to update the water balance model. The spatio-temporal module comprises a computer watertable simulation model and routines providing linkage between event data and GIS thematic layer for event-based analysis. Specialized data processing routines have been developed to link the network data model with temporal hydrological modeling to allow computation of important network parameters such as flow travel time, discharge and capacity, and to dynamically simulate drainage response to individual rainfall events. A common interface has been developed to link those components and functions, the system is well suited for assessment and management of agricultural drainage systems. In the second paper, case studies are presented which show how the system can be used for efficient agricultural drainage management, such as drainage capacity assessment, discharge computation, and event-based acid drainage evaluation and management. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Drainage networks, and the associated channel links and drainage basins, are fundamental concepts in earth science. Drainage channels are the lines along which fluvial processes act to transport water and mineral material out of a local region, allowing gravity processes on slopes to continue to lower landscapes. Drainage networks are the basis for defining drainage basins, an essential component in hydrological models and resource management plans (O’Callaghan and Mark, 1984).

An agricultural drainage system, such as the drainage system in the McLeods Creek estuary floodplain in northern New South Wales (NSW), Australia, can be described as a network of artificial and natural drains. It is composed of links representing linear channels of flow and nodes representing their connections. To manage water resources in such an environment, common management practices often deal with network problems such as assessment of drainage capacity, computations of water flow rate and discharge, and estimates of pollutant loading and distribution. This is particularly the case when studying acid drainage problems associated with the acid sulfate soils (ASS) where the accumulation of toxic acid products may be discharged through the drainage network and cause major environmental disasters (White et al., 1993).

The assessment of ameliorative management strategies requires the analysis of the current drainage system and prediction of the potential consequences of changes to various hydrological factors, such as rainfall events. To enable these to be assessed and monitored in a quick and efficient way, computer-based spatial analytical capabilities are needed. Geographic information systems (GIS) have shown their potential for developing the database and computational models for drainage network analysis, and coordinating floodplain planning (Schultz, 1993; DeVantier and Feldman, 1993; Djokic and Maidment, 1993; Duan and Mao, 1995).

Network analysis has been an important part of today’s GIS analysis and modeling capabilities. However, to date its major applications have been in the areas of urban and facility management (e.g. resource allocation and infrastructure planning), particularly transportation modeling. There are significant weaknesses and limitations in applying this analysis for water resource studies related to resource and environmental management (Djokic and Maidment, 1993). The most significant problem is that there is no implicit relationship between the magnitude of traffic flow and the impedance or resistance to flow, as is normally assumed in water flow routines. Furthermore, as the traffic direction on each network link has to be pre-determined manually when establishing the network model, it is time-consuming and error prone, particularly in a flat area, to construct a drainage network where the direction of water flow is fundamentally controlled by the drain elevation and control structures. Despite these limitations, the GIS network analysis still has an obvious potential to model and simulate the characteristics of drainage in a flat landscape environment.

In this study, the focus is on the agricultural drainage network in a floodplain environment. The agricultural drainage system, such as the drainage system in our study site, has these characteristics: (1) it is a hybrid system since it contains different types of drains (e.g. field drains, union drains, and pipes) which have different characteristics; (2) it is a dynamic system in which the watertable changes seasonally as weather and land
use change, so do the drainage flow direction and velocity; and (3) it is an open system since overland flow may occur making a part or whole network cease functioning at a given period of time. These characteristics of the agricultural drainage network make it more difficult to be described and simulated in a GIS environment.

To address these problems, a specific agricultural drainage network model has to be developed to represent the real-world agricultural drainage system and to meet the specific requirements of the agricultural drainage network analysis. Specialized data processing routines need to be developed to link network data model with hydrological models to allow computation of important network parameters such as flow travel time, velocity and discharge. This paper presents such a system, termed the integrated drainage network analysis system (IDNAS), and its implementation. The application of the system is presented in the second paper.

2. The integrated drainage network analysis system

The integrated drainage network analysis system (IDNAS) is a combined hydrological modeling of the water balance and the surface-water system using efficient computer models for each component, linked spatially and temporally, to enable the spatio-temporal simulation of an agricultural drainage network (Fig. 1). This system comprises three principle components: (1) an agricultural drainage network module, which is the core of the system, and is managed in a GIS containing a network analysis module and the interface with other modules; (2) an evapotranspiration (ET) model developed specifically for the intended application to obtain spatial distribution of ET from remotely sensed data; and (3) an event-based spatio-temporal module which comprises a computer watertable simulation model and routines providing linkage with GIS thematic data layer on event bases.

The integrated system performs five tasks: (1) digital data gathering; (2) GIS operations; (3) model input data processing; (4) hydrological simulation; and (5) output processing and visualization. The system is capable of both event-based and continuous hydrological simulations. It facilitates the evaluations of various water management and planning measures to control acid runoff and pollutant loading into river systems. The system includes a user interface developed for the specific simulation processes and

Fig. 1. A conceptual diagram of IDNAS.
visualization. The interface provides interactive menus that allow users to select a particular location, time interval, enter and modify specific model parameters (e.g. roughness and runoff coefficients) for simulation. Default values, measured or empirical, are also included in all of the operations of the user interface that allows the processes to be executed without stopping due to the user’s lack of knowledge on those input parameters.

There are three types of data required for the IDNAS: spatial (GIS), temporal, and program execution control data. The spatial data are remote sensing images and GIS data layers including watertable elevation, surface elevation, watershed and sub-basin delineation, crop blocks information, impervious soil layer elevation, outflow control points and the spatial drainage network. Temporal data are time series data of acid outflow events and watertable depth derived from the outputs of the temporal hydrological models such as DRAINMOD (Skaggs, 1980) and RADCALC (Jupp, 1992). Program execution control data are a series of batch programs, such as Arc Macro Language (AML) and C codes, which handle all the operations and the model-data interactions.

2.1. The agricultural drainage network module

The agricultural drainage network module is an extended GIS network model to represent the components and characteristics of a real-world network system and to perform specific network analysis in water resources. The key to produce such a network model lies in the understanding of the relationship between the characteristics of a physical network system and the representation of those characteristics by the elements of the network model.

For the drainage network model established for this study, the network elements include three generic features: network links, network nodes and centers (Fig. 2). Network links are channels of flow representing the interconnected conduits (drains or pipes) and they are connected to each other at network nodes. Network nodes are endpoints of network links and they represent the drain intersections. A center is a location which supplies water throughout the network, or it receives a supply of water from the network. For example, the location of a floodgate or outlet can be regarded as a center through which the water enters into a river or another drain.

Each link connects with two nodes: start-node and end-node depending on the drainage flow direction. In a transportation network, the travel direction is mandatorily determined.

![Fig. 2. Basic elements of an agricultural drainage network in an estuary floodplain environment.](image-url)
In an agricultural drainage network, the magnitude and direction of water flow is fundamentally controlled by water levels at the two ends of a drain except with drainage barriers (e.g. gates). The water levels of the drain are subsequently controlled by the water levels in the crop field depending on the soil water balance. The water balance is, in turn, greatly influenced by land use and evapotranspiration, and it changes with time. Therefore, the water levels of the drain can be viewed as a function of time and they can be simulated using a temporal water balance model.

In relation to the network elements (links, nodes and centers), their network properties are impedance, resource demand and capacity. The link impedance is the amount of resistance that has to be overcome to travel from one end to the other and it is referred to as the flow travel time between the two ends (time of concentration). Unlike a transportation network in which the flow can be bi-directional, the flow of a drainage network is uni-directional at a given time, assuming water flowing up-hill is impossible. The most significant difference here, however, is that the amount (sometimes the direction as well) of impedance can be varied from time to time as a function of changing hydraulic conditions such as changes in water levels in the drains caused by a rainfall event. Therefore, for an agricultural drainage network it is not appropriate to predetermine the values of link impedance and it should be treated as a function of the water levels and, subsequently, a function of time. Resource demand only exists within the network link element and it is defined as the amount of water flowing in a link (drain or pipe) for a given impedance limitation. Capacity measures the total amount of flow that can be supplied to a center to meet a given limit. When links are allocated to a center, their amount of flow is accumulated.

Consider a drainage network in a floodplain environment, where drains are presented as links with their impedance defined as the time required for water flow to pass through the links. This time is in turn controlled by the hydraulic gradient of the drain water and channel roughness. The outlet of the catchment is a floodgate which can be represented as a center with its capacity defined as the accumulated flow, which increases the difference between water levels inside and outside gate (thus the pressure on the gate), required to push the gate open for discharge. For conditions of quasi-steady state flow, the hydraulic gradient in the drain is both constant and comparatively small, thus the flow regime is uniform (constant velocity) and the impedance tends to be constant. A rainfall event may result in an increased hydraulic gradient which in turn makes an increasing flow velocity, so that the impedance becomes smaller, causing a larger amount of water flowing through the network in a shorter period of time. At the center, when accumulated flow makes a large-enough pressure on the floodgate, the floodgate opens and discharges the drain water into the river system.

To model the agricultural drainage network, its surrounding hydrological environments should be taken into consideration. As the case of the estuary floodplain hydrological environment, it consists of three major components: the land surface (here refers to cane block), the outflow control point (OCP) which refers to the inner side of a pipe linking the filed drain with surface drain or union drain, and the water conveyance system - the drainage network, consisting of pipes, and different types of channels (Fig. 3). Each of these elements requires a different database structure, and can be represented as one of
the three standard GIS graphical features (polygons, points, and lines). Each of these geometric features has a database in the form of feature attribute table attached to it describing its physical attributes, thus forming three unique GIS data layers.

The definition of OCP is of significance both in hydrology and in GIS representation. OCPs are the boundary conditions controlling water outflow into the drainage network. The elevation at OCP is the outflow control elevation and the outflow will happen only if the water level in the field exceeds this elevation. Significant drainage does not occur until the surface of the watertable reaches the outflow elevation when water can flow from the field drain at the edge of the block into the main drain (the McLeods Creek in this case). The drainage below this point is non-zero but can be ignored. OCPs connect the surface (polygon) and sub-surface drainage paths (line), and convey water from the cane blocks into the drainage network. If the OCPs cannot convey all the water from surface to the drainage network, then flooding occurs.

This representation of the framework provides the flexibility required for efficient incorporation of possible changes in any of the databases. Change of a value of a property, such as watershed’s runoff coefficient or time of concentration, has to be updated only in one database. Changes can be made either during database creation and verification or later, during comparative analysis of different drainage network design alternatives.

2.2. The evapotranspiration module

One of the important characteristics of an agricultural drainage network is that it is an open system and it is greatly influenced by the surrounding crops and their seasonal
changes. The evapotranspiration must be taken into account in studying the drainage
network since it is a dominant factor influencing watertable position which controls the
acid drainage and outflows (White et al., 1993). An approach on remote sensing
estimation of sugarcane ET (vegetation index and temperature trapezoid, VITT) has been
developed and presented in Yang et al. (1997). Based on this approach, a specific AML
program (ALLET.AML) has been developed to estimate ET from Landsat TM image and
easily obtainable meteorological data. This program, together with the interactive
program between ET and other components, form the ET module which estimates ET
from remotely sensed data, performs water balance computation, and updates the
watertable database (refer Fig. 4).

The typical soil (acid sulfate soils) profile in an estuary floodplain contains an
impermeable estuary clay layer (saturated hydraulic conductivity is about 1 mm/h)
(White et al., 1997). The water balance of such an environment is a simple accounting
procedure for estimating water entering and leaving an area. When the whole watershed
is considered as a system, the lateral inflow and outflow can be ignored. Thus, the water
balance for a non-irrigated floodplain, with a shallow watertable and no deep drainage,
over any given period (e.g. daily) can be expressed as

\[ WTD = WTD_0 + P - ET - R, \]

where \( WTD \) is the watertable depth from the ground surface (mm), \( WTD_0 \) is the initial
watertable depth (mm), \( P \) is precipitation (mm), \( ET \) is the evapotranspiration (mm), and \( R \)
is surface runoff (mm). In the dry periods, evapotranspiration is the dominant factor
influencing the watertable falls and a calibration coefficient (\( z \)) is estimated from the
specific yield of the soil (number of mm of water input/output per mm of watertable rise/
fall) to adjust the watertable fall. After the computation of \( WTD \), the watertable elevation
(mm, AHD) (Australian height datum) can be easily obtained by subtracting \( WTD \) (mm)
from the surface elevation (mm, AHD).

If the remote sensing image is available at the time of the simulation, the ET can be
computed from the image (Yang et al., 1997) and directly entered into Eq. (1) for \( WTD \)
computation. It is often difficult and not applicable to obtain remotely sensed data for
each run of the water balance simulation. For practical applications, assuming that the
average daily ET is constant during a specific growing season or period, the remote
sensing data are only to be collected for the major growing seasons or whenever there is a
significant change of the crop pattern such as harvest and change of varieties. Even in
case of the complete absence of remote sensing data for a whole season (an extremely
rare situation), the ET of different land cover type may still be approximated through
computer programs (such as RADCALC, Jupp, 1992) and constant values may be applied
to each cover type to generate an ET coverage.

2.3. The spatio-temporal module

The only data model available within existing GIS’s that can be viewed as a spatio-
temporal data model is a series of ‘snapshot’ images. This model is not well-suited for
analyzing overall temporal relationships of events throughout a geographical area as a
temporally-based representation. For this study, an event-based approach is conceptually
adopted from Peuquet and Duan (1995). In this approach, the time associated with each change is stored in increasing order from the initial ‘world state’ at time $t_0$ to the latest recorded change at time $t_n$. These may be recorded at any desired temporal resolution (or time step). In this work, however, only daily and monthly intervals are of interest and they are then used to form the event lists. Associated with each $t_i$ are the changes (in this case, rise and fall of watertables) which occurred between $t_{i-1}$ and $t_i$, except that the entire ‘base map’ is pre-prepared with the first record time $t_0$. Each event list and associated changes relate to a single thematic domain (e.g. watertable levels) which is represented by a polygon data layer since it is more suitable for representing the farm blocks and their watertable status in the central point required by DRAINMOD.

The base map, initial watertable elevation (WT$_0$), is determined from the surface elevation and WTD$_0$ which can be measured or simulated using a computer program (e.g. DRAINMOD). Although the time step is not necessarily to be uniform, the selection of $t_0$ should be as close as possible to $t_i$. Once the base map is created, any change in watertable elevation is then calculated from the initial WTD$_0$, based on the soil water balance.

Agricultural drainage networks are typically dense and complicated, such as at McLeods Creek which has 523 drains with a drain density of 21.6 km/km$^2$. It will be a prohibitive amount of work for each block to be recorded, measured or processed with the watertable simulation model (in this study, DRAINMOD). Studies (White et al., 1997; Yang, 1997) show that there exists a noticeable relationship between the pattern of watertable fluctuation and the drain spacing, particularly when the drain space is less than 75 m. These suggest that the cane blocks can be grouped into fewer categories by their drain spacing (such as 5 categories: <40, 40–50, 50–60, 60–70, and >75 m), which significantly reduces the computation time but returns reasonable accuracy (less than 10 cm difference in watertable, Yang, 1997). Note that the accuracy depends on the grouping detail level, more groups more accurate. The drawback of this approach, like any generalized method, is the loss of detailed information. In the implementation of this method the number of groups should be adjusted to best represent the real situation. Furthermore, the grouping interval is not necessarily to be the same. For example, a denser interval should be applied to the smaller drain spacing group since the smaller drain spacing has greater influence on watertable than that of the sparser one.

The linkage of the event list and the thematic data layer is achieved through the updating of the watertable attributes using the relevant values from the simulation model (DRAINMOD). That is, for a given time (day of year, DOY or MONTH), each group of drain spacing in the watertable coverage is associated with a corresponding watertable depth value in the event file. Once the watertable values are updated by this means, the updated coverage can then be entered into the network model for event-based drainage network analysis.

### 3. The implementation of IDNAS

#### 3.1. The implementation

The integrated drainage network analysis system (IDNAS) has been implemented with an Arc/Info GIS (Fig. 4). Arc/Info GIS’s network routines were used with a specially
defined database and attributes. The following section presents the implementation of these database and attributes that comprise the network model and framework.

In Arc/Info, network link and arc are synonymous and they have the same attribute name, arc attribute table (AAT). Link impedance (flow time) and link demand items are implemented in the AAT. Rather than pre-determined, the link impedance is determined from the watertable levels at both ends for each drain. The watertable levels vary with time and can be simulated using a watertable simulation model (DRAINMOD). The demand item is defined as the amount of water flowing in a drain, and it is also determined by the watertables in the drain and it varies with time. Thus, both link impedance and demand can be viewed as functions of time.

The locations and attributes of centers are recorded in an INFO file, referred to as center file. Center attributes contain two important network-specific items: water

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Fig. 4. The implementation scheme showing the modeling processes of IDNAS.
resource capacity and impedance limit. The water resource capacity of the center is the maximum amount of water that can be supplied to or from a floodgate or outlet. The impedance limit is represented by the maximum travel time of water from the remotest drain to the watershed outlet.

The land surface is represented by a polygon data model that defines the cane block (BLOCK, polygon coverage) which connects with an OCP. This polygon coverage contains attribute items which give the basic block information such as block area, owner and variety. This coverage can be interacted with other polygon data layers to obtain more information essential for the hydrological modeling, such as runoff coefficient (C-value), time of concentration, watertable (WT), designed discharges (such as for 2 and 10 year return periods).

The drainage network (DRAINNET, line coverage) was created by digitizing high-resolution aerial photos. The elevation data at both ends (F-AHD, T-AHD) of the drains were obtained from a field survey and manually added to the AAT. The open drain dimension (e.g. bottom width, radius, across area), roughness and pipe size are also measured and encoded into the AAT which in turn are used to estimate the water flow rates, time of concentration (TC-DRAIN) and drain capacity (Q-MAX). The differentiation among different types of drains was made by using a special item (DRAIN-TYPE) in the AAT. This differentiation enables grouped property assignment, drawing or analysis to be applied to a class of drains instead of being applied to all of them.

The outflow control points (OCP, point coverage) were determined from the nodes in the drainage network coverage (DRAINNET) through an automatic process (Yang, 1997). Information on pipe diameter and OCP elevation were obtained and encoded into the database from field survey. Values of other items were calculated from the available information on the point attribute table or other attribute tables (e.g. DRAINNET.AAT and BLOCK.PAT) through a commonly related item. The importance of this coverage lies in its bridging function connecting surface and drainage network.

The linkage of these databases is achieved through the use of a common item among them. This is a unique name (OCP-ID) assigned to each OCP which enables database join using intrinsic Arc/Info commands. Since OCP hydrologically connects surface and drainage network, i.e. they belong both to the surface terrain as inlets and to the drainage network as sources, they are the natural features to select for database integration. Each of the three databases has an item with an OCP-ID name. For OCP, this is its unique identifier, for drainage area (block) this is a name of the inlet that drains that particular area, and for the drainage network this is a name of the inlet that directly contributes to the flow in that drain. A master INFO file was also created which bridges among these databases and the temporary watertable data (Fig. 5), and also acts as a backup of these links.

3.2. The display interface

Implementation of IDNAS relies on specialized graphical user interfaces. The interface is designed here to bridge among the system components and provide an overall control of model processing, with an emphasis on two-way sharing of information between GIS and DRAINMOD for event-based simulation. The entire system has been integrated
through a menu-driven interface within the Arc/Info GIS’s ARCPLOT environment, allowing interactive spatial feature display and updating. A series of AML programs have been developed and embedded into the system to perform all automated data processing tasks such as data selection, analysis and simulation. The AML programs call external programs for various hydrological modeling tasks, and display the results interactively using Arc/Info ARCPLOT utilities. Fig. 6 presents the framework of such an interface.

The highest level of the interface shows the sequence of menu choices based on functions (e.g. draw, query, model, event and network). Draw allows users to display a series of relevant GIS coverages, such as sugarcane blocks, sugarcane varieties, drainage networks and terrain map of the watershed, as well as remote sensing images. Queries on the feature attributes of the displayed coverage can also be made for any interesting location. The model menu includes two sub-programs (RADCALC and DRAINMOD) which simulate the time-varying hydrological parameters, such as evapotranspiration and watertable depth. Event provides an interface for event-based simulation of acid outflow events, which incorporates remote sensing ET operation and WTD thematic layer updating. Network modeling is the central task of this work, and it consists of three sub-programs which perform different functions as drainage capacity assessment, drainage flowrate computation, discharge and water quality simulation. Interactive menus is provided for the selection of outlet location, Manning’s coefficients and drain types (DRAIN or PIPE). Calibration option is also provided in the computation processing within the network module to ensure the network settings are correct.

The interface was developed using the current version (7.1.1) of the Arc/Info software running on a SUN/UNIX platform. However, many of the methods developed here can be
generalized to other GIS software with little difficulty, assuming such software has the ability to access external programs. The emphasis here is that the computer modeling process can be embedded within a GIS with the display functions acting as the interactive user interface for all inputs and outputs for the specific purposes.

The drawback of this method, however, is that interface programs are specific for the involved programs, and if other programs are to be used, a new set of interface programs needs to be made. A better solution is that there is a generic data transfer structure that every model uses without the need to know how other programs will utilize...
those data. Use of look-up tables for display of time-variant results is convenient and efficient.

4. Discussion and further studies

This study has developed an IDNAS using integrated technology of hydrological modeling, remote sensing and GIS. A specific agricultural drainage network model has been created. This is an application therefore oriented network model, which is different in many ways from the transportation network for which the original GIS network functions were developed. Although the terminology is much alike with that of the current GIS network models, it has more specific meaning and representations for the agricultural drainage system. By these definitions, the real agricultural drainage network can be adequately described and modeled.

Remote sensing techniques have been used in this study for evapotranspiration estimation. The aim of the study was to provide a simplified method for local ET estimation and to update the soil water balance in the drainage network simulation. Using the combination of the VITT concept and Landsat TM data, a simple method has been developed for assessing the variation of the actual ET rate in a local scale over the sugarcane fields (Yang et al., 1997). This method has been integrated with IDNAS (as the ET module) and proven to be efficient for water balance updating, which is crucial in drainage network modeling. The use of a GIS-based system allows the direct use of remotely sensed estimates of ET that would not be possible with tradition point-based modeling systems.

Time-variant simulation is not well suited for direct implementation within current GIS because the present GIS database is static and it lacks the temporal analysis capabilities. To address these problems, an interactive hydrological model-GIS system has been developed. This study has shown that the combination of GIS and hydrological models can be used in event-based drainage network simulation, and to meet the needs for the specific agricultural drainage problems.

Although the system was originally developed for a floodplain environment, it comprises the generic components (water conveyance system, outlet, farm block) for any agricultural drainage system. More importantly, this study created the common interface and automatic linkage among those components. Thus, the system is applicable to other similar agricultural drainage systems provided that each module is properly modified to meet the specific environment under consideration.

In future studies, to accomplish a complete linkage between GIS and hydrological models would require the GIS to have time-dependent data structures so that the evolution through time of the spatial distribution of hydrological phenomena could be readily observed. In linking the GIS and hydrological model, an object-oriented data model seems to be a useful intermediate step between the spatial-relational model inherent in GIS and the data structures of the hydrological model. Expert GIS, with its linkage between object-oriented and spatial-relational models may be a useful tool in achieving this linkage.

In the second paper, the system will be used for practical agricultural drainage management, particularly in acid drainage monitoring and control. Four practical
applications will be given: verification and assessment of the capacities of the existing drainage network; determination of the drainage flow isochrones to the watershed outlet; estimation of pollutant allocation and accumulation for a given watershed outlet; and simulation of the acid outflow events.

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