Integrating GIS and Modelling Soil Water and Crop Production

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EXTENDED ABSTRACT

Most soil/water/crop growth models are based on the 1-D conceptualization paradigm and lack the spatio-temporal dimensions advocated in recent times. The literature abounds with agricultural systems models that are based on point scale or paddock scale soil water balance coupled to a crop growth process. Some of these models were adapted to represent lumped characterization of spatial processes. They are ideal for simulating crop development on a relatively homogeneous area such as a paddock. To account for spatial heterogeneity over a larger area such as an irrigation district or a river basin, new techniques are required. The spatial dimension of agricultural production systems makes geographic information system (GIS) software a powerful tool for developing sustainable management solutions. GIS technology provides a mechanism for spatial data input/storage and display with intervening soil water and crop growth engine. A prototype model has been developed to link SWAGMAN-Destiny (Soil Water and Groundwater Management) model to a component based development framework provided by Arc-GIS engine. SWAGMAN-Destiny is a point scale soil water balance and crop growth simulation model with crop growth affected by water, salt and aeration stress. The model represents a point in the landscape, and uses capacity concepts to describe the principle processes that determine the fluxes of water and salt into and through a soil profile. Ability to compute a reasonable water and salt balance over time is used to check for integrity of the calculations. The generic crop growth model simulates canopy development using intercepted radiant energy and ambient temperature as the major drivers. Growth, and ultimately yield, is modified from a nominated potential by invoking daily stress factors induced by water deficit, aeration stress, salt stress and nitrogen deficit. Partitioning of growth between shoots and roots and the distribution of roots in the layered soil profile is also influenced by the limiting stress factors.

The development of this model attempts to encapsulate our best understanding of the major controlling processes in this complex irrigated production system and allow us to examine the consequences of a range of management options aimed at influencing both productivity, and soil, salt and water management. The model is able to quantify year-to-year variation in yield using long-term weather data and thus may be used for risk assessment. In addition, the model is able to determine the leaching fraction expressed as a percentage of total infiltration at different levels of the soil profile.

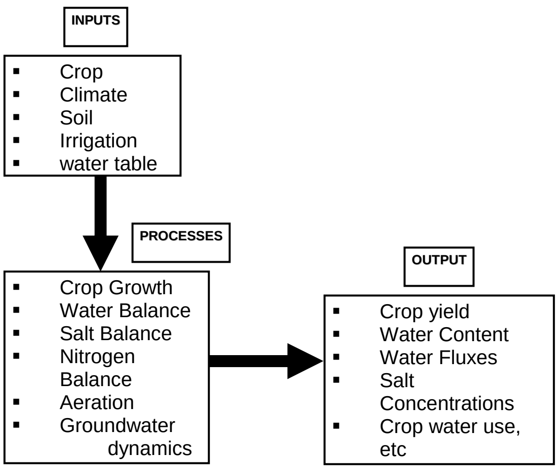

Figure 1: SWAGMAN – Destiny model Inputs, processes and outputs.

The integrated model uses software components, in Arc Objects, within the .NET programming environment. This paper addresses the development history of the model in addition to an overview of GIS and SWAGMAN modelling components

1. INTRODUCTION

Irrigation generates on-farm benefits for the irrigators but alongside can imposes costs on third parties, including the downstream communities and the environment. The issue can be modelled as a negative externality problem. The externalities exist in situations where the activity of one person affects or spills over onto another, without compensating the latter (Baumol & Oates 1993). In many irrigation areas, the return flows containing dissolved salt and other pollutants are either directly shunted to streams or enter the unconfined underground and adjacent aquifers–a common property resource. Farmers often over-irrigate which acerbates these issues; farmers have an incentive to use more water to enhance production while society has the opposite incentive to reduce water use to mitigate potential negative impacts on the environment. Where the aquifer recharge exceeds their natural assimilative capacity over long periods, the damages to the supportive capacity of the resource base become inevitable, compromising productivity. In terms of irrigation management for waterlogging and salinity mitigation the sustainability goal would mean a net zero change in groundwater table and salt balance by modelling spatial water and salt balances under the cropping systems.

Computer based biological simulation models describe the bio-physical interaction between crop/soil/atmosphere system under different management scenarios. The integration of biological simulation models into a GIS framework enhances the interpretation and understanding of model results in the spatio-temporal context. The GIS framework provides an environment of visualization of model results using farm or regional maps. The modelling unit (feature polygon) can represent a field (paddock), farm or the entire region. For each modelling unit, different management options can be assigned to evaluate the effect of crops, soil type, climate and groundwater level conditions on various environmental factors such as water leaching through the root zone or different levels within the soil profile. Several attempts at integrating GIS into a biophysical model have been made such as AEGIS/WIN (Agricultural and Environmental Geographic Information System for Microsoft Windows) described in Hoogenboom et al. (1999) where the CERES crop growth models and DSSAT framework was coupled to a GIS system. Furthermore Ascough II et al. (2004) described AgSimGIS, an integrated GIS and Agricultural System Modelling where the root zone water quality model (RZWQM, Ahuja et al., 2000) was coupled to a GIS framework. In addition, Robertson et. al. (2005) described a modified version of AgET that was coupled to ArcGIS 9.0 to map estimated recharge across the lake Warden Recovery Catchment (LWRC) on the south coast of Western Australia. We present in this paper a framework that couples a comprehensive crop growth, soil water and salt balance model to a GIS system. The model's executable is invoked for each modelling unit and the output is collated and joined to the polygon attribute tables of the shape file representing modelling domain. The user interface developed can be used to:

1. define crop, soil, weather , ground water level conditions and management options and assign them to modelling units (polygon features)

2. create thematic maps of yield, actual crop evapo-transpiration, rainfall etc

3. perform simulations and examine outputs.

The framework uses a comprehensive crop/soil/climate model SWAGMAN-Destiny written in FORTRAN and modified to run using management scenarios assigned to each modelling unit (polygon features).

2. SWAGMAN-DESTINY MODEL

Projecting trends in growth and yield from a range of crops, grown with different irrigation practices in a variable climatic environment where the irrigated areas are underlain with shallow saline watertables is a demanding and complex task. This task requires some form of simulation model with the capability not only to represent the key driving processes but also to analyse the long-term effect of management practices. The principle aim is to predict change, evaluate trends and indicate the uncertainty range in biophysical variables such as crop leaf area development, yield, salt distribution and groundwater recharge. The SWAGMAN® (Salt Water And Groundwater MANagement) series of models was developed to achieve policy goals such as regional salinity balance (Khan et al, 2003).

This paper describes SWAGMAN®-Destiny, a soil water and watertable model, coupled to a generic crop growth model. The model represents a point in the landscape, and uses capacity concepts to describe the principle processes that determine the fluxes of water and salt into and through a soil profile. The ability to compute water and salt balance over time within reasonable accuracy limits is used to check for integrity of the calculations. The generic crop growth model simulates canopy development using intercepted radiant energy and ambient temperature as the major drivers. Growth, and ultimately yield, is modified from a nominated potential by invoking daily stress factors induced by water deficit, aeration stress, salt and nitrogen deficiency. Partitioning of growth between shoots and roots and the distribution of roots in the layered soil profile is also influenced by the limiting stress factors.

The development of this model attempts to encapsulate our best understanding of the major controlling processes in this complex irrigated production system and allow us to examine the consequences of a range of management options aimed at influencing both productivity, and soil, salt and water management. The model is able to quantify year-to-year variation in yield using long-term weather data and thus may be used for risk assessment. Complementary papers describe the testing and validation of the model and show the results from various scenarios encountered in irrigated agriculture. In many irrigated areas of the world, there are signs of declining productivity as the result of land and water degradation. This decline is often associated with the interrelated processes of water table rise and the onset of soil salinization. Salinization is the process leading to an increase in the concentration of soluble salts within the crop root zone. This occurs when salts accumulate in the root zone faster than they can be leached, often due to impeded drainage. Salinization is exacerbated as capillary upflow brings dissolved salts from saturated soil layers (the water table) up into the unsaturated soil of the root zone. In turn, the increased concentration of salt in the root zone affects the growth and development of crops and hence reduces yield and farmers return.

In Australia, more than 2 million hectares of land is irrigated. The extent of the irrigated area which has or is predisposed to having watertables less than 2 meters from the ground surface is not known exactly but most irrigated areas in the southern half of mainland Australia either have already, or will have shallow water tables present within 20 years. The depth to the water table from the ground surface is influenced by underlying piezometric pressures, soil properties, weather, irrigation and crop management. With variable water table and salinization conditions, estimating yields from a range of irrigated crops and projecting likely productivity change over time is difficult and must consider many factors. Soil conditions, irrigated water quality, drainage (both surface and sub-surface), underlying piezometric conditions in addition to agronomic and irrigation management will all have an influence. With this complex of interacting factors, predictive capability is only possible with process simulation. Simulation models that are able to represent the effects of these factors can provide the capability to examine the sensitivity of yield estimates to any of these factors and in turn provide a way of exploring different management scenarios. This capability, if general enough, can assist in developing options for improved management in irrigated areas where salinity and shallow water tables are issues.

While much work has been done in describing soil processes of salinization, comparatively little work has been done in the area of developing models of plant response to salt and/or waterlogging in temporally variable field conditions. Most of the work in this area has been devoted to examining crop tolerance to salinity which is typically described as relative yield reduction from salinity increases (Bernstein, 1975; Maas and Hoffman, 1977).

The simulation model that is described here, SWAGMAN Destiny, is designed to simulate the balances of water and salt in the soil/plant/atmosphere system and their effects on crop productivity. (Godwin et al. (In prep), Xevi et.al. (In prep). The model has evolved from the SWAGMAN Whatif program (Robbins et. al., 1995) and from experience with using the CERES crop growth models for cereals (Ritchie et. al., 1989) in the irrigation areas of Australia.

2.1 Model Description

SWAGMAN-Destiny is primarily used to examine the consequences of particular crop and irrigation management scenarios on the soil water and salt status, on the depth and salinity level of the water table and on crop productivity. The model contains procedures for the simulation of crop growth, water balance and the balances of salt and nitrogen. It simulates processes at a point and operates on a daily time step. An important design criterion for the model was the need to simulate a diversity of irrigated crops and to minimise the input data requirements. To achieve this, a generalised growth routine was developed which simulates the processes of canopy and root growth (see Jones et. al., 1991).

2.2 Crop Growth

A common growth model is used to simulate the leaf area development, biomass growth and root proliferation of the following crops: wheat, maize, soybean, sunflower, rice, cotton, grape vines, eucalypt woodlots, deciduous fruit trees, Lucerne and grazed pastures. It simulates crop response to water deficit, water logging (soil aeration), soil salinity and nitrogen (for wheat, maize, sunflower and cotton only). It assumes a homogeneous crop stand with sufficient population of plants to realistically achieve the ceiling value of leaf area index that is given as an input to the model. The model, while using some components of the comprehensive crop growth model, CERES (Singh et al 1989), does not have the capacity to simulate response to population or development of individual yield components. The model uses a common suite of routines for every crop with species-specific inputs to describe crop differences.

2.3 Soil Water Balance

The SWAGMAN Destiny model uses soil water balance as described in Ritchie (1985) and Ritchie and Otter-Nacke (1985). Changes to the original model include an infiltration routine (Broadbridge and White, 1987) and process descriptions to account for impeded drainage. Also included are process description for drainage of water into tile drains, defining the location of the water table, and the effect of the underlying groundwater pressure head. Water and salt balance is estimated daily within a five-meter soil profile that is divided into fifteen layers of varying depths. Layers are thin near the surface where changes in water content are most rapid and thick at the bottom of the profile where water content changes are slow. Most of the crops simulated take up water within the upper two metres of soil.

2.4 Estimation of potential evaporation.

Potential evaporation is estimated using a modified Penman-Monteith approach from daily weather records using coefficients and methods described in Meyer et. al. (1994). At minimum, the data requirements are solar radiation, maximum and minimum temperatures. If wind speed and relative humidity data are available, a modified Penman equation is used to estimate potential evaporation.

3. SWAGMAN GIS DESCRIPTION AND DEVELOPMENT

Swagman GIS is under development using Microsoft Visual Studio .NET 2005 and the C# language. GIS functionality is obtained through linkages to the COM callable wrappers around ArcObject classes. ArcObject is the platform on which the ArcGIS family of applications rely, providing data management, map presentation functionality. Through COM interfaces exposed by these wrappers, MapControl and TOCControl can be embedded in the application and will function the same way as they do in ArcView. Pre-authoring of Shapefiles may be done in ArcGIS desktop applications or other software. Shapefiles of land units can be loaded into the application where the polygon ID's will be read and made available for assigning SWAGMAN-Destiny input scenarios for simulation. Figure 2 shows the main application screen using the MapControl and TOCControl of the ArcObjects controls.

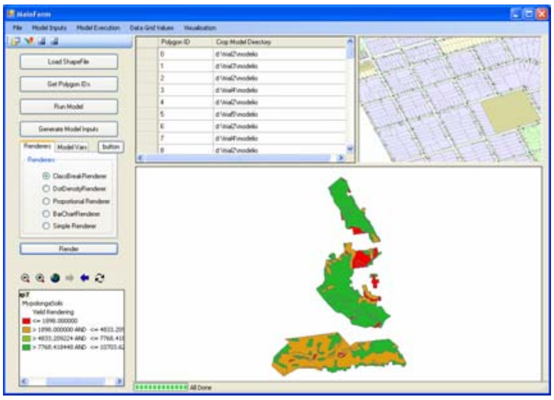

Figure 2: Main Application screen

ShapeFiles are loaded using the **LoadShapeFile** Button and the polygon ID's will be read and placed in an editable grid. Using the **Generate Model Inputs** button, a comprehensive input generation form for SWAGMAN Destiny model shown in Figure 3 appears. The form contains tabs for input of model structural parameters like simulation start date, length of run, number of simulations and output frequency. In addition, the tabs include weather, crops, soil and initial ground water specification. The completed input files may be saved in a user defined directory indicated by **Output Directory** in Figure 3. Crop model input files can then be attached to the feature id's of the shape file in an editable grid.

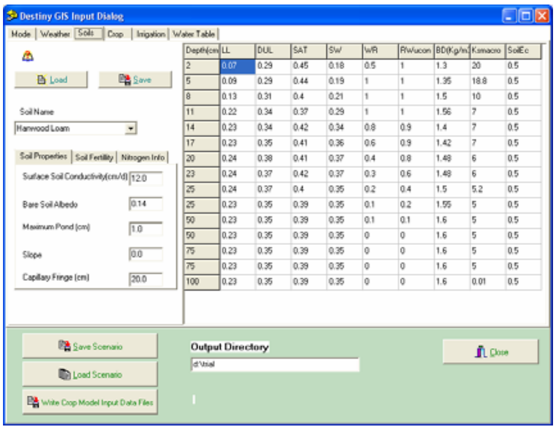

Figure 3: Crop model input specification

The crop growth and water balance model can be executed using the **Run Model** button. The results of all the simulation runs are extracted from the ASCII files generated and inserted into the polygon attribute table of the shapefile for thematic mapping. Figure 4 shows a screen where desired variables (yield, irrigation amount, evapo-transpiration (ET) etc. can be plotted for up to six polygon features.

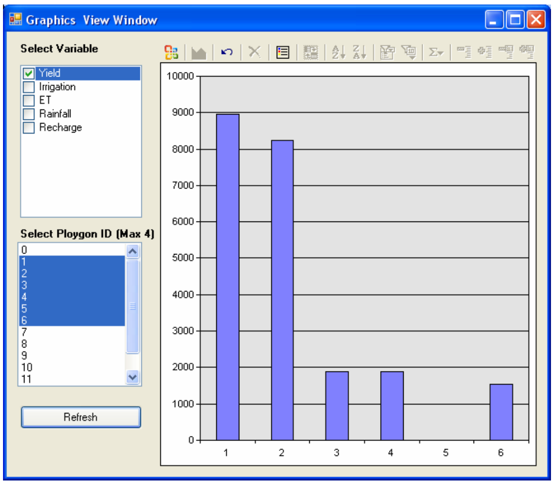

Figure 4: Graphic output visualisation screen for some feature Id's.

4. DISCUSSION

Integrating ArcGIS tools into crop growth/water balance models are essential for analysing and displaying bio-physical quantities in the spatial domain. A sharp contrast to the one-dimensional analysis currently used by many bio-physical models. In addition, we are able to visualise spatially the effect changes in climate, soil and land use on recharge below the root zone. Furthermore biophysical variables can be viewed and compared on a feature basis all in one place. It is anticipated that this model will be able to help benchmark irrigation water use efficiency and environmental performance of irrigation area over space and time.

5. CONCLUSION

The SWAGMAN Destiny model with a GIS functionality provides a tool for spatial data input and simulation to manage crop productivity watertables and salinity in irrigation areas. SWAGMAN Destiny simulates crop growth, water and salt balance over the landscape while the GIS functionality provides spatial visualisation of results. The integrated framework will provide synergy between geospatial and temporal agricultural information that aids decision making for local and regional planners. In addition, the integrated model will assist in the presentation and understanding of soil/water and crop growth variables on a spatial scale. The use of ArcObjects in the development of the model enables the application to be ported without the need for ArcView software although there are licence requirements that need to be fulfilled before the wider distribution of software.

6. ACKNOWLEDGEMENTS

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