CLASS Spatial Analyst: A GIS Based Tool for Distributed Hydrological Modelling

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ABSTRACT

CLASS Spatial Analyst is a GIS tool which can be used for spatial modelling. The tool generates a number of spatial layers that can be used for many practical applications. These include climate zoning, multi-resolution DEMs, Topographic Wetness Index (TWI) / Compound Topographic Index (CTI), lateral multiple flow paths, accumulation and dispersion of water and solutes from hazard areas, estimation of soil depth, soil material/horizon distribution and soil moisture storage capacity in different parts of the landscape.

The technology used in this tool is supported by various international and national publications (eg. Tarboton, 1997; Gallant and Dowling, 2003). The tool also generates all the input files required by other models that are currently being developed and tested under the CLASS modelling framework. In particular, the multiple flow path algorithms determine the computational sequence that drives the water balance model to transfer water and solutes from upslope properties to the downslope properties and eventually to the catchment outlet. Additionally, the spatial distributions of the soils, landuse, climate and groundwater flow systems (GFS) link grid cell scale dynamics to the catchment scale effects.

CLASS Spatial Analyst is part of the CLASS (Catchment scale multiple-landuse atmosphere soil water and solute transport model) modelling framework which consists of a suite of tools required for physically based distributed eco-hydrological modelling. The Department of Natural Resources (DNR) and the Cooperative Research Centre for Catchment Hydrology (CRCCH) have developed the CLASS framework. The CLASS model, its components and their algorithms are described in a detailed technical report (Tuteja et al., 2004). The tools from the CLASS framework can be used to investigate the effects of landuse and climate variability on both paddock scale and the catchment scale.

Spatial Analyst is supported by a user friendly Windows based graphical users interface (GUI). The current version is available free of cost from DNR, NSW and is operational on ArcGIS 8.3 and the Microsoft .NET platform. By September 2005, the tool will be made operational under the TIME environment developed by the CRCCH (Rahman *et al*., 2003) and will be available for free download from the CRCCH Catchment Modelling Toolkit website (http://www.toolkit.net.au/class).

This paper outlines the basic concepts behind CLASS Spatial Analyst, describes the various functionality and presents some of the results for its application to the Little River Catchment. The details (step by step) for implementing CLASS Spatial Analyst are described in CLASS Spatial Analyst User Manual (Teng *et. al*., 2004).

1. INTRODUCTION

In collaboration with the Cooperative Research Centre for Catchment Hydrology, models are being developed by the Department of Natural Resources for analysing and assessing the impact of combinations of land uses (e.g. forestry, grazing, cropping) on small to medium sized catchments (2000-5000 km^2) in the medium to high (400 to > 1000 mm/year) rainfall zone of south-eastern Australia.

The CLASS catchment model is a fully distributed model and is designed to predict the hydrologic effects of landuse change and climate variability. The model design is adapted to Australian conditions for accurate assessment of the paddock scale effects of landuse changes and climate variability on water and solute yield from the catchment. The approach differs from earlier approaches in that the model is designed to operate in data poor environments with the appropriate level of complexity. It recognises the need for a robust spatial architecture and all the required functionality has been built into the CLASS Spatial Analyst.

The model operates at the grid cell level and includes a series of processes and sub-models. At the core of these models are modules that simulate photosynthesis and respiration, and tissue growth, turnover and senescence of crops, pastures and trees. When fully implemented, the models will be linked through a GIS interface to provide a grid cell-scale mosaic of land use impacts for evaluating the whole-catchment outcomes.

CLASS Spatial Analyst is the GIS tool which prepares/constructs all the input datasets required by other CLASS modelling tools. Based on the catchment Digital Elevation Model (DEM), it determines the sequence in which computations / calculations need to be done on individual grid cells within the catchment to compute catchment scale fluxes. It also generates a catchment file which associates each grid cell in the catchment with appropriate landuse, climate variables, soil type and soil hydraulic properties, total soil depth and soil depth for each soil material / horizon, soil salinity and it map each grid cell to the respective Groundwater Flow System (GFS).

CLASS Spatial Analyst can also be used as a stand-alone GIS tool to provide multiple spatial layers for many other practical applications, such as: delineating sub-catchments and stream network; estimating the spatial distribution of soil depth across the catchment; estimating soil moisture storage capacity for a catchment; and delineating and targeting appropriate areas within a catchment for management interventions (eg. salinity, soil erosion, etc).

The CLASS suite of tools will be used to guide investment decisions for Catchment Management Authorities, evaluating outcomes against investments, as well by other clients such as local Government, inter-agency Commissions such as the Murray-Darling Ministerial Council, and for specific purposes such as environmental reporting.

2. CONCEPTS

The main objective behind the development of CLASS Spatial Analyst is to provide hydrologists and catchment modellers with a scientifically credible GIS tool which hides all the complexity of the computation algorithms behind a user friendly graphical user interface (GUI) and guides them step by step in applying it to the catchment of interest. The complete details for applying CLASS Spatial Analyst along with its application to one example catchment (and all the results) are described in the CLASS Spatial Analyst User Manual (Teng *et. al.*, 2004).

The approach we have followed in the application of Spatial Analyst on catchments across NSW is to store all the available input layers such as climate, landuse, DEM, etc for the entire state in the background. When a user creates a new project, the GUI prompts the user to select the gauging station / outlet (either directly on the map or by entering the gauging station number). Once the outlet is selected, the program will generate the catchment for that outlet and clip all the available input layers in the background to the generated catchment boundary. The complete application of CLASS Spatial Analyst involves implementation of a number of functions to the entire catchment. Some of the major ones are described below.

2.1. Generate Catchment Boundary

This step includes filling sinks, calculating D8 flow direction, flow accumulation, stream network, snap pour point, generating watershed, and buffering watershed.

- Fill sinks in the DEM

The presence of sinks may result in an erroneous flow-direction grid. This function fills all the sinks in the input DEM and creates a

depressionless DEM which is the desired input to the D8 and D. (Tarboton, 1997) flow direction functions. It identifies all sinks in the DEM and raises their elevation to the level of the lowest pour point around their edge. Sub-steps within this step include: determine flow direction; find sinks; find contributing area above each sink; find depth of sinks; fill sinks to the value of the lowest boundary cell in the watershed of each sink; and repeat these sub-steps until there are no more sinks.

- Generate D8 flow direction

The D8 flow direction function calculates and assigns a flow weight to each grid cell in the catchment such that each grid cell flows to only one of the eight neighbouring grid cells with the steepest descent / slope.

- Generate D8 flow accumulation

In this sub-step, it calculates the number of grid cells contributing to each grid cell in the catchment and assigns this value to this grid cell as D8 flow accumulation.

- Generate D8 stream network

This function delineates the D8 stream network for the catchment using the results from D8 flow accumulation and a user defined threshold value. There is a user configurable parameter in Tools -> Option called stream threshold where the user can input their own threshold and delineate different levels of stream.

- Snap outlet to stream

Sometimes the gauging station / catchment outlet does not fall on the stream network because of errors in data recording. This function overcomes this problem by snapping the gauging station to the cell of highest flow accumulation within a specified neighbourhood. The user can define the radius of this neighbourhood in the Option window.

- Generate D8 watershed

This function marks out all the grid cells contributing to the snapped catchment outlet and generates the catchment boundary and watershed. The contributing area for each grid cell is taken as itself plus the upslope neighbours that drain in to it. This is evaluated recursively starting from the catchment outlet and moving back inside the catchment.

- Add a buffer to the generated watershed

This function adds a buffer around the generated watershed. The purpose of this step is to avoid edge effects. The width of the buffer to be put around the catchment is a user configurable parameter and the user can enter the value through the interface.

2.2. Use D8 to calculate CTI

This step includes calculating D8 flow direction, contributing area, catchment boundary, Compound Topographic Index (CTI) or Topographic Wetness Index (TWI), generating computation sequence, and influence and dependence area diagram for selected grid cell or group of grid cells (area).

- Generate D8 flow direction

The D. approach assigns each grid cell with a flow direction based on steepest slope on a triangular facet (Tarboton, 1997). The flow from each grid cell drains either to only one neighbouring grid cell (if the angle falls along a cardinal or diagonal direction, or is on an angle falling between the direct angle to two adjacent neighbours) or two neighbouring grid cells (if the angle is different to above limits). In the latter case the flow is proportioned between these two neighbouring grid cells according to how close the flow direction angle is to the direct angle to those grid cells.

- Generate D8 contributing area

This function calculates the contributing area for the multiple flow direction D. approach using a recursive procedure. The contribution at each grid cell is taken initially as one unit. The contributing area of each grid cell is then taken as its own contribution plus the contribution from upslope neighbours that have some fraction draining to it.

- Generate D8 catchment boundary

This function marks out all the grid cells contributing to the catchment outlet and generates the catchment boundary and watershed based on D. methodology.

- Calculate compound topographic index (CTI) for each grid cell

This function calculates CTI (also referred to as TWI) for each grid cell within the watershed.

- Generate computation sequence

This function determines the computational sequence based on the multiple flow path algorithms. The computational sequence drives the water balance model in the CLASS catchment model to transfer water and solutes from upslope properties to downslope properties and eventually to the catchment outlet.

- Generate influence and dependence area diagram for selected grid cell or salt scald

Dependence function determines the grid cells contributing to the selected grid cell or salt outbreak. Each of the contributing grid cells is given a weight (between 0 and 1) based on their relative contribution to the selected grid cell or salt scald.

Influence function determines the downslope path or the grid cells to which the selected grid cell contributes (eventually reaching the catchment outlet).

2.3. Climate Zone

This step includes clipping drill points from climate surface within the catchment, associating climate data with spatial locations, performing interpolation, climate zone delineation and computing daily climate file for each user specified climate zone.

- Clip climate data drill points (from SILO, Jeffrey, *et al.*, 2001) within the catchment boundary

Daily climate data is available for the whole of Australia (SILO, Jeffrey, *et al.*, 2001). The climate folder provided in the background datasets contains daily climate data drilled from SILO at 5 km grid resolution for the whole of NSW. For any catchment within NSW, this function will automatically clip the correct drill points within the generated catchment boundary. If the catchment is outside of NSW, the user will have to input the appropriate climate data.

- Associate climate data with the appropriate drill point

This sub-step searches for the appropriate climate files for the clipped drill points, calculates average annual rainfall value for each point and joins this field with the geographic feature.

- Interpolate between points to generate daily and annual climate surfaces

This function uses the annual rainfall field associated with the geographic features as control points and spline as an interpolation method to get a smooth rainfall surface.

- Delineate climate zones based on user specified rainfall bands

This function reclassifies the generated climate surface into different climate zones based on the rainfall bands entered by the user (Table 1).

- Generate average daily climate file

This function clips the climate files associated with each of the climate zones specified by the user and generates average daily climate files for each of these zones.

2.4. Soil Depth

This function estimates the total soil depth and soil depth for each soil material / horizon for all the grid cells in the catchment using CTI, MrVBF (Multi-resolution valley bottom flatness index) (Gallant and Dowling, 2003) and soil parameters (based on soil landscapes, Table 2). Calculations for soil depth are based on the methodology of McKenzie et al. (2003) and the details and formulations used are explained in details in Teng et al. (2004) and Murphy et al. (2005a, 2005b).

2.5. Soil Salinity

This function assigns Soil-EC (electrical conductivity) to each soil material / horizon of all the grid cells in the catchment based on FLAG landforms (Summerell et al., 2003), FLAG UPNESS index (Roberts et al., 1997), salt outbreak mapping and soil-EC parameters (based on soil landscapes, Table 3).

3. DATA

3.1. Input Data

Spatial Data:

The main input for Spatial Analyst is Digital Elevation Model (DEM) (NSW LIC, 1999).

Soil Landscapes map for the catchment. There is a unique value field associated with this spatial layer which joins the two soil parameter files (for calculating soil depth and soil salinity) with the geographic feature.

FLAG Upness Index, used to distribute soil EC.

Salt outbreak map, used to distribute soil EC among saline and non-saline areas.

MrVBF output, used to calculate MrVBF soil depth (McKenzie et al. 2003).

Other data:

A .dbf table (Table 1) with rainfall bands, which is used to delineate climate zones.

Table 1. Rainfall bands

ID	Out Field	From Field (mm)	To Field (mm)
1	1	0	640
2	2	640	690
3	3	690	740
4	4	740	1000

Table with parameters to estimate soil depth and soil material/horizon distribution (Table 2).

Table 2. Soil depth parameters

Soil Depth Parameters							
Soil Landscape	d5 (m)	d50 (m)	da5 (m)	da50 (m)	da95 (m)	lamda1 (-)	lamda2 (-)
1	6	6	0.3	0.35	0.4	1.5	2
2	4	6	0.3	0.35	0.4	1.5	2
3	0.5	1.5	0.1	0.15	0.2	1.5	2
4	0.3	1.5	0.25	0.3	0.35	1.5	2

Table with parameters to distribute soil salinity among saline and non-saline areas in the catchment (Table 3).

Table 3. Soil depth parameters

'EC 1:5 (dS/m)					
'Soil material	Soil Landscape	Non-saline min EC	Non-saline max EC	Saline min EC	Saline max EC
1	1	0.03	0.1	1	2
1	2	0.03	0.1	1	2
1	3	0.06	0.08	1	2
1	4	0.03	0.04	1.5	3

3.2. Model Outputs

Spatial Data:
- Filled DEM, D8 flow direction, D8 flow accumulation, stream network, snaped outlet, watershed, buffered watershed;

- D∞ flow direction, D∞ contributing area, CTI, D∞ watershed, influence and dependence diagram for a user defined point or area;

- Clipped drill points, rainfall surface, rainfall zones;

- Total soil depth, soil depth for each soil horizon;

- Soil salinity for each soil horizon.

Other Data:
- Climate file which contains average daily climate data for each climate zone;

- Grid cell sequence file which associates each grid cell in the catchment with appropriate landuse, climate variables, soil type and soil hydraulic properties, total soil depth and soil depth for each soil material / horizon, soil salinity and map each grid cell to the respective Groundwater Flow System (GFS).

4. IMPLEMENTATION / APPLICATION

CLASS Spatial Analyst is used in a number of major studies across NSW. It has been applied to more than 30 catchments across NSW ranging in size from 10 to 7500 km^2.

- Snowy Monaro Plantation Strategy

Spatial Analyst has been implemented on Delegate, Bombala and McLachlan catchments. The total soil depth and depth for each soil horizon from this implementation was used to define the modelling domain for all the pasture and tree growth simulations. The soil moisture capacity estimated by Spatial Analyst for each of the three catchments was used to guide implementation of catchment scale lumped rainfall runoff model.

The Snowy Monaro Plantation Strategy is being developed in partnership between the NSW Premiers Department and DNR and has been established to provide a balance between the agriculture and forest industries of the Southern Monaro Region. This work will provide policy input to the Plantations and Reafforestation Act.

- Living Murray Initiative

Spatial Analyst is currently being implemented on the Koondrook-Perricoota Forest to estimate spatial distribution of soil depth and overland flow patterns. This is done as part of The Living Murray Initiative that will explore and implement the structural works required to gravitate water from Torrumbarry Weir into the Koondrook-Perricoota Forest (KPF). The forest covers an area of approximately 32,000ha on the NSW side of the Murray River between Echuca-Moama and Barham-Koondrook.

- GRDC Project

It has also been implemented on Simmons Creek catchment, which is the focus catchment for a Grain Research and Development Corporation funded collaborative project (CSIRO Land and Water, NSW DPI, and NSW DNR). The soil depths estimated from Spatial Analyst will be used to define the soil domain for crop and pasture growth models.

- MDBC Salinity Audit Update 2004-2005

CLASS Spatial Analyst has been implemented on 8 focus catchments used in the MDBC Salinity Audit Update 2004 under the MDBMC Basin Salinity Management Strategy and Murray-Darling Basin Agreement, Schedule C. The outputs from the model are used to define 2 dimensional transects across these focus catchments for MODFLOW implementation.

Where possible, the outputs from CLASS Spatial Analyst are validated against available datasets. Field validation was done for soil depths estimated by Spatial Analyst in the Snowy catchments of Delegate, Bombala and McLachlan and it demonstrates that Spatial Analyst was able to estimate the soil depth across all the catchments reasonably well (Murphy et al., 2005a, 2005b).

Some of the results (output maps) from the application of CLASS Spatial Analyst to Little River catchment in the Macquarie basin of NSW are presented in Figure 1.

5. CONCLUSIONS

CLASS Spatial Analyst is a GIS tool which can be used for spatial modelling. It hides all the complexity of the computation algorithms behind a user friendly graphical user interface (GUI) and guides the user step by step in applying it to the catchment of interest.

It prepares/constructs all the input datasets required by other CLASS modelling tools. CLASS Spatial Analyst can also be used as a stand-alone GIS tool to provide multiple spatial layers for many other practical applications, such as delineating sub-catchments and stream network, estimating spatial distribution of soil depth across the catchment, estimating soil moisture storage capacity for a catchment, and delineating and targeting appropriate areas within a catchment for management interventions.

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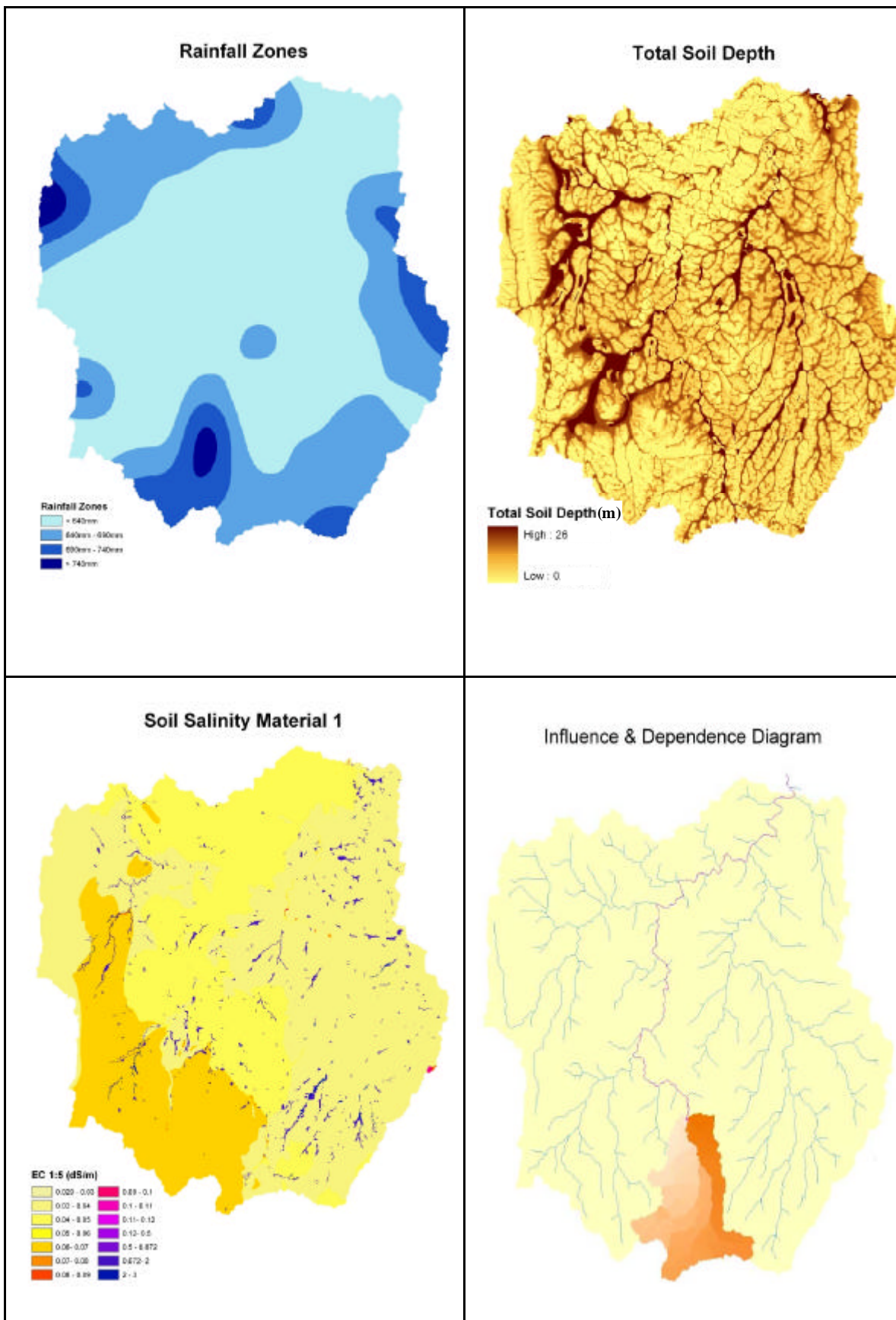
Figure 1. Rainfall Zones, Total Soil Depth, Soil Salinity and Influence & Dependence diagram.