The CLASS Modelling Framework: A platform for distributed eco-hydrological modelling

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EXTENDED ABSTRACT

This paper describes development and testing of the components of a distributed eco-hydrological modelling framework CLASS (Catchment Scale Multiple-Landuse Atmosphere Soil Water and Solute Transport Model). The CLASS modelling framework, its components and their algorithms are described in a detailed technical report (Tuteja et al., 2004; available for download from Catchment Modelling Toolkit website http://www.toolkit.net.au/class). CLASS can be used to predict land-use effects at paddock, hillslope and catchment scales. Effects of climate scenarios predicted by stochastic climate models as well as the effects of spatio-temporal climate variations within a catchment can also be analysed. CLASS can be used for water balance, solute balance, vegetation growth and terrain modelling. Recharge-discharge dynamics, lateral flow and streamflow can also be modelled using CLASS.

CLASS uses "bottom-up" modelling approach and offers an alternative to the commonly used simple "top down" modelling approaches. Distinctive features of CLASS include grid cell based analysis and the ability to allow for interactions within the model structure between energy (turbulent and radiation exchange), vertical and horizontal redistribution of soil moisture, plant growth, surface and groundwater fluxes, transport of conservative solutes and streamflow routing. Sufficient tools and databases exist in the CLASS framework that can be used for generating the information generally not available for catchment scale implementations (eg. flow path, soil depth, climate zoning, pedotransfer functions etc.). Tools in the CLASS modelling framework can be implemented easily at the hillslope scale. However, at the catchment scale, CLASS is a computationally demanding modelling approach and requires good understanding of the modelling concepts.

New South Wales Department of Natural Resources has developed the CLASS framework. The work formed part of the Cooperative Research Centre for Catchment Hydrology (CRCCH) Associate Project. CLASS is supported by a windows based user friendly graphical users interface (GUI). It is fully object oriented and has been developed on Microsoft.Net platform. Considerable effort has been made in representing vegetation growth as well as in the pathways that water takes from hillslope to stream. The framework consists of seven tools of which three are available for free download from the CRCCH Catchment Modelling Toolkit website (about 430 downloads to date). Three other CLASS modelling tools would be available through the Toolkit web site by December 2005 and the catchment model would be available by June 2006. All modelling tools in the CLASS framework (with the exception of 3PG+) have been developed as an integral part of CLASS using comprehensive and published scientific methods. State of the art numerical, scientific and software development technologies have been used. CLASS has been peer reviewed by experts in distributed eco-hydrological modelling.

1. INTRODUCTION

Investigation of the vegetation effects in the atmosphere-soil-vegetation continuum on the catchment scale water balance has been a subject of extensive observation and modelling across the world for many years (Vertessy et al., 1996). Complex distributed parameter process models such as SHE and TOPOG_IRM (Dawes and Hatton, 1993) have been used to address these issues. While very useful, they require comprehensive calibration data sets to parameterise the many micro-scale processes incorporated in their procedures. As such they are used primarily as research tools rather than management tools. Process based one dimensional water balance models such as APSIM, have been used in a GIS framework to investigate the effects of soils, landuse and land management practices on the near surface soil moisture dynamics and water balance components (Ringrose-Voase and Cresswell, 2000). However, there is often a mismatch between the catchment scale fluxes and those obtained in a purely vertical analysis due to scale effects and no accounting of the lateral fluxes.

A new generation of the distributed hydro-ecological models has been developed or is under development that attempt to simplify the complexity of applying a tightly bound theory and iterative numerical computations as in SHE and TOPOG. These models attempt to simplify excessive parameterisation and the numerical complexity associated with the distributed models. The structure of these models still retains the relevant internal processes of the climate-vegetation-soil-topography continuum and the relevant boundary conditions within the modelling paradigm. Examples of these models include various implementations of the TOPMODEL (Beven and Freer, 2001), DHSVM (Wigmosta et al., 1994), MACAQUE (Watson et al., 1999) and CATSALT (Tuteja et al., 2003). Most of these models do not have any vegetation growth component and they depend on other models for this information (eg. leaf area index LAI and biomass).

Evapotranspiration is a major component of the water balance that depends on vegetation type, growth and management. Therefore a seamless integration of hydrology with vegetation growth modelling components is required within a grid-cell based model structure to predict landuse impacts at the catchment scale. CLASS offers such an alternative wherein established and well-tested Richards' equation based hydrology is coupled with practical and sound vegetation growth modelling components. At the core of vegetation growth models are modules that simulate photosynthesis and respiration, and tissue growth, turnover and senescence of crops, pastures and trees.

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. Some of the projects where CLASS tools are being used include the following: Snowy Monaro Landscape Strategy (NSW), The Living Murray Initiative (Koondrook Perricoota Forest, NSW), Urban stormwater model development (Monash University, Vic), Siang hydro-power project (India).

2. COMPONENTS OF THE CLASS MODELLING FRAMEWORK

The CLASS modelling framework consists of a suite of tools that can be used for physically based distributed eco-hydrological modelling (Figure 1). The framework is designed for investigation of the effects of landuse and climate variability on both paddock scale as well as the catchment scale. The framework is developed on .Net platform and includes the following tools that are used as building blocks in the catchment model. Some examples from implementation of CLASS are also illustrated in the following sections.

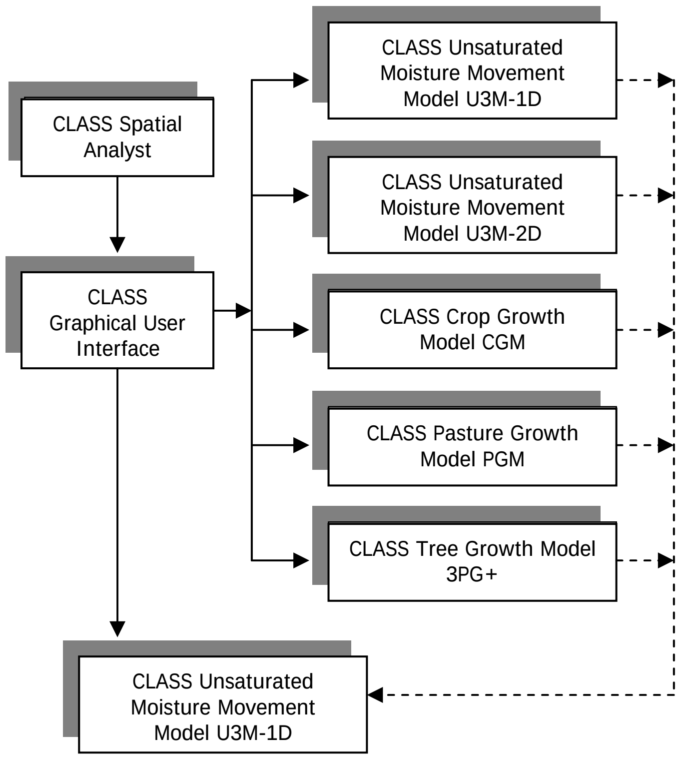

Figure 1. Schematic diagram of the CLASS Modelling Framework.

2.1. CLASS Spatial Analyst (SA)

CLASS Spatial Analyst is a fully automated GIS based tool which can be used for spatial modelling (Teng et al., 2005). A stand-alone version of SA that depends on ARC GIS8.3 for spatial visualisation was released in May 2004 and the Toolkit version is due for release by December 2005.

Widespread availability of the 25m DEM in Australia has led to a variety of GIS based hydrological modelling activities. However, procedures relating to spatial modelling work (eg. calculation of climate surfaces, terrain indices, influence and dependence diagrams) are generally performed using either adhoc mechanical procedures or disjointed programs without a coherent and fully automated object oriented structure.

Spatial Analyst overcomes these limitations and can be applied easily on large catchments. The technology used in this tool is supported by various international and national publications (eg. Tarboton, 1997; McKenzie et al., 2003). It prepares all spatial information required by the catchment model. This includes: preparation of the climate surface and delineation of the climate zones, soil depth, water balance computational sequence using multiple flowpaths from terrain analysis and flow accumulation areas, wetness index, land discharge areas, soil salinity distribution and mapping of grid-cells to landuse and groundwater flow systems (GFS). A dynamic but constant user specified grid cell size can be used depending on DEM resolution and size of the problem.

Climate surface and soil depths generated from SA for the Delegate sub-catchment in the Snowy River catchment are shown in Figures 2 and 3 respectively. Daily climate data at 5km grid within the catchment is clipped automatically from the background data sets and average annual rainfall for each point is computed. Spline interpolation is performed to get a smooth rainfall surface for the grid cell size specified by the user. Climate zones are then delineated based on the user specified rainfall bands and average daily climate file for each climate zone is generated. Soil depths are determined using the methodology of McKenzie et al. (2003) and Murphy et al. (2005;this issue). Soil depth for each grid cell is first computed based on terrain indices designed for erosional (wetness index) and depositional (MRVBF) landscapes. A smooth weighting function is then used to predict the soil depth. More weight is given to wetness index for areas high in the landscape. The weighting for wetness index decreases gradually while weighting for MRVBF increases for locations low in the landscape.

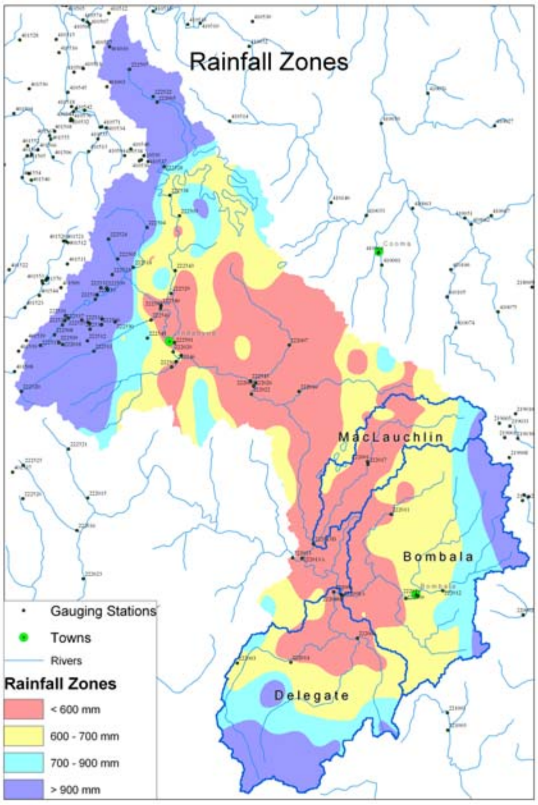

Figure 2. Delineation of climate zones in the Snowy catchment. (CLASS Spatial Analyst)

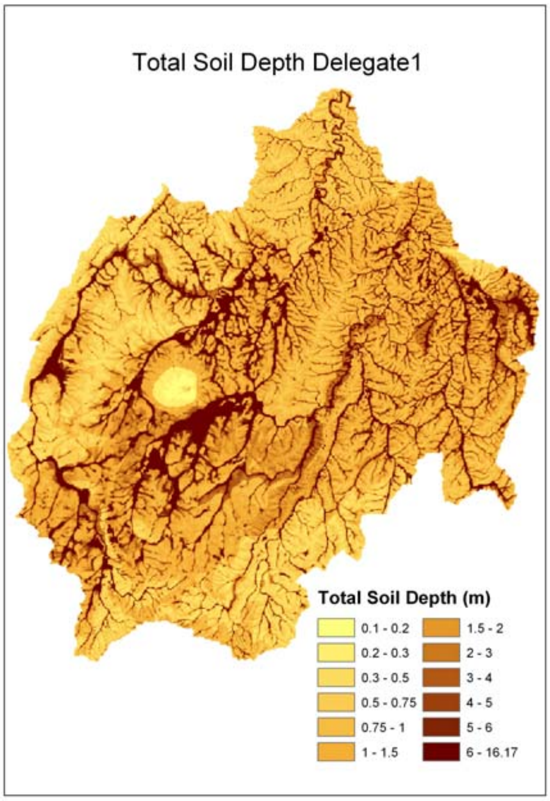

Figure 3. Total soil depth for the Delegate sub-catchment, Snowy River catchment. (CLASS Spatial Analyst)

2.2. CLASS Water Balance Model U3M-1D

CLASS U3M-1D is a variable sub-daily time step model used for partitioning water balance in the unsaturated zone using the Richards' equation on a single grid cell (Vaze et al., 2004a; released June 2004). Solutes are transferred between the soil materials using advection. U3M-1D is similar to the concepts used in HYDRUS-2D (Šimunek et al., 1999). Water balance at a given grid cell for a layered soil profile can be defined by the Richards' equation (1) and Darcy's law (2).

$$\frac{\partial\theta(z,t)}{\partial t} = -\frac{\partial \vec{q}_v(z,t)}{\partial z} + S(z,t) \qquad (1)$$

$$\vec{q}_v = -D(\theta)\frac{\partial \theta}{\partial z} - K_V(\theta) \qquad (2)$$

where, $\theta =$ volumetric water content ($m^3.m^{-3}$), $\vec{q}_v =$ Darcy flux in the vertical direction ($m.s^{-1}$), $S =$ algebraic sum of the water sources and sinks expressed as volume of water per unit control volume per unit time (s^{-1}), $D(\theta) =$ hydraulic diffusivity ($m^2.s^{-1}$), $K_V(\theta) =$ unsaturated hydraulic conductivity along the vertical axis ($m.s^{-1}$).

The source/sink term includes moisture loss by transpiration by the overstory and the understory, soil evaporation and moisture gain from the horizontal flow from the upslope areas. Neumann Type II time dependent specified flux upper boundary condition is used at the soil surface. A separate boundary condition is used for the recharge and discharge areas on the land. In the recharge areas, flux from the lower boundary is taken as minimum of the flux under unit gradient from the bottom soil layer and hydraulic conductivity of the sub-surface material. In the discharge areas, a specified flux boundary condition is used.

Comparison of soil moisture simulated from CLASS and HYDRUS at 200 cm (from bottom) in a 230cm homogeneous soil profile is shown in Figure 4. Simulations were done for 180 days with no plant water stress in both models. Results on soil moisture variation for each 10cm layer across the soil profile, actual plant transpiration and leakage from the soil profile were within 0.5%. For the case of heterogeneous soil profile, simulations were done for daily climate data from 1975-2000 (26 years) and a soil profile from the Little River catchment (Macquarie River basin, New South Wales). Simulations were done with plant water stress in both models. Results on soil moisture within each of the four soil materials were within 0-2% and at the interface of the material were within 0-5%. These differences are largely due to differences in numerical architecture of the two models and plant water stress function implementation in the two models (soil moisture based plant water stress function in CLASS U3M-1D as against pressure based soil moisture stress function in HYDRUS).

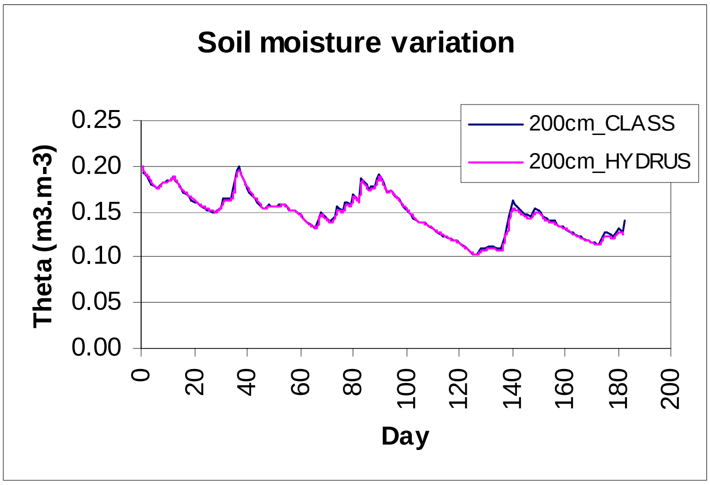

Figure 4. Comparison of soil moisture at 200cm from bottom of a homogenous 230cm soil profile. (U3M-1D)

2.3. CLASS Water balance Model U3M-2D

CLASS U3M-2D is a variable sub-daily time step model used for partitioning water balance in the unsaturated zone using the Richards' equation on a hillslope (equation 1 applied along the vertical plane). Water balance is performed along the vertical as in U3M-1D and excess water, if any, is transferred downslope within the respective soil material using unsaturated form of the Darcy's law. Solutes are transferred between the soil materials using advection.

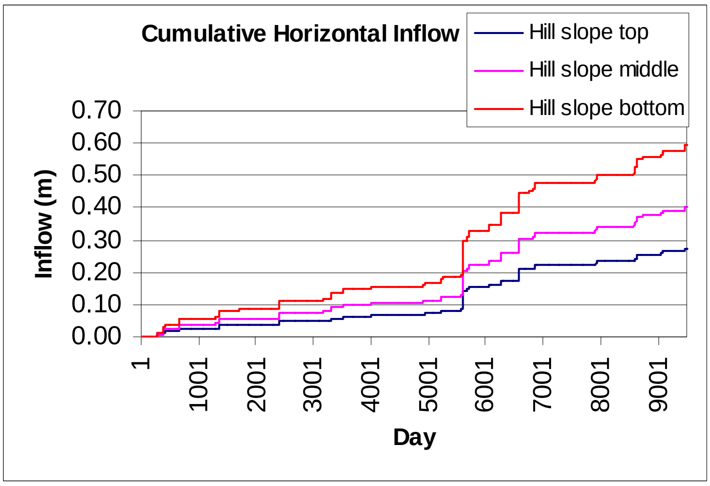

Figure 5. Cumulative horizontal inflow over 26 years in the soil material 2 (from bottom) of a heterogeneous 225m long and 2.3m deep soil profile with 5% slope. (U3M-2D)

U3M-2D was tested on a range of hillslopes (5-25%) and lengths (100-500m) for a heterogeneous soil profile with 4 soil materials from the Little River catchments. Comparison of cumulative horizontal inflow into soil material 2 (from bottom) of a 225m long and 2.3m deep soil profile on a 5% slope over 26 years is shown in Figure 4. This extra soil moisture progressively increases downslope and is available for evapotranspiration and/or leakage from bottom of the soil profile and/or lateral throughflow.

2.4. CLASS Pasture Growth Model PGM

CLASS PGM is a daily time step growth model based on Johnson (2003) that simulates up to five multiple pasture species (Vaze et al., 2004b). These pasture species may be annual or perennial, temperate (C3) or tropical (C4), grasses or broad leaf. Environmental conditions as well as soil water, nutrient and salinity status influences pasture growth and tissue dynamics.

PGM allows the user to incorporate the season of growth (summer versus winter) and a range of grazing management strategies to simulate the feedback effects of grazing on plant growth and hydrological fluxes. Default parameters for generic pasture species are included. Information relating vegetation growth (eg. biomass, root distribution, LAI and ground cover) is passed each day to the water balance component U3M-1D. Comparison of green, dead and total herbage mass obtained from a 25-year PGM simulation for a 5-species mix pasture is shown in Figure 6. See Vaze et al. (2005; this issue) for details on calibration of PGM to field data sets.

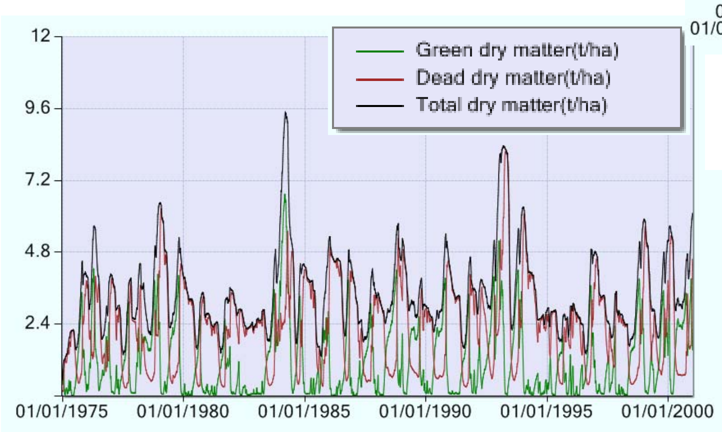

Figure 6. Variation of green, dead and total herbage mass in t/ha from a 25-year simulation for 5-species mix pasture. (PGM)

2.5. CLASS Crop Growth Model CGM

CLASS CGM is a daily time step growth model based on Johnson (2003) that provides options for modelling the main field crops grown in Australia (Vaze et al., 2004c). Physiological structure of CGM allows for complex interactions between light, temperature, available water and nutrients. The crop module is developed for a range of species types. Temperate C3 crops such as wheat, barley, canola and sunflowers and tropical C4 crops such as sorghum and maize can be simulated. Simulated crops may be determinate or indeterminate (that is, whether leaf production and growth continues after the onset of flowering).

Default parameters for generic crop species are included and sowing schedule is an input to the model. Crop germination, flowering and maturity (harvest) are defined as dates. Temporal variation of grain yield, shoot and root dry weight, live and dead LAI are simulated. Comparison of green, dead, total herbage mass and grain yield obtained from a 25-year CGM simulation for wheat crop is shown in Figure 7.

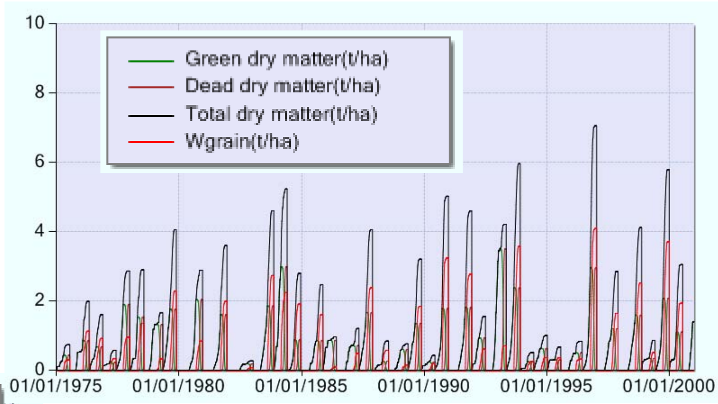

Figure 7. Variation of green, dead, total herbage mass and grain yield in t/ha from a 25-year simulation for the wheat crop. (CGM)

2.6. CLASS 3PG+

CLASS 3PG+ simulates tree growth using the 3-PG+ model (Morris, 2003), an adaptation of the 3PG model by Landsberg and Waring (1997). The tree growth component operates at a monthly time step (adapted from 3PG+) and the water balance component (U3M-1D) operates at a sub-daily time step with same values for the tree growth state variables for each day in a given month.

Variation of LAI from CLASS 3PG+ model for pine plantations for 4 climate zones 566 mm/y, 690 mm/y, 857 mm/y and 1324 mm/y from Figure 2 in the Snowy catchment is shown in Figure 8. State variables such as biomass, root distribution, ground cover and LAI from 3PG+ is passed once every month to U3M-1D for simulating water balance at a daily time step. Established industry standard tree growth model 3PG+ is combined with the Richards' equation based water balance model CLASS U3M-1D.

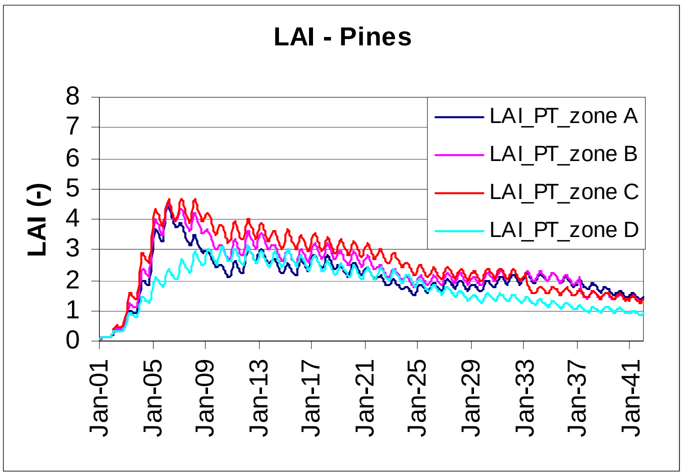

Figure 8. Comparison of LAI for pine plantation for 4 climate zones: 566 mm/y, 690 mm/y, 857 mm/y and 1324 mm/y. (CLASS 3PG+)

2.7. CLASS Catchment Model

CLASS Catchment Model is a distributed model that operates on a grid-cell level and is described in a detailed CRCCH technical report (Tuteja et al., 2004). All the above CLASS tools have been developed and tested on a range of problems. Work is currently in progress on completion of the catchment model. When fully implemented, the models will be linked through a GIS interface to provide catchment scale impacts based on a grid-cell mosaic of landuse.

Climate data and landuse information is used at each grid cell on each day for vegetation growth using CLASS PGM, CGM and 3PG+. Unsaturated zone water and solute balance is then performed using U3M-1D along the vertical axis (equations 1-2) with the appropriate boundary conditions. Excess moisture and the associated solutes are then estimated over each soil material in a 3-dimensional spatial architecture. Water and solutes are transferred from up-slope properties to down-slope properties and eventually to the catchment outlet using multiple flow paths (Tarboton, 1997) and Darcian concepts. Additionally, spatial distribution of soils, landuse, climate and groundwater flow system (GFS) links grid-cell scale dynamics to the catchment scale effects. Recharge and lateral throughflow each are pooled over the GFS. A proportion of each of these components is passed to the land as surface discharge and the remaining component is passed to the stream. Discharge to the land and stream is lagged appropriately and is based on the assumption that bulk of the travel time results from flow under phreatic conditions and that a fast pressure transmission signal applies under confined conditions. Routing in the stream is based on the response function approach.

The model design accounts for data constraints often imposed in catchment scale investigations. Data requirements vary depending on the type of implementation ie. property scale or the catchment scale. The following primary data are required for implementation of the CLASS framework: climate data, DEM, Landuse, FLAG upness index, MRVBF index, GFS spatial distribution, hydraulic properties and solute concentration, soils spatial distribution, soil hydraulic properties, growth parameters, observed flow and solute concentration. Most of these data are available on a wide spread basis. Sufficient tools and databases exist in the CLASS framework that can be used for generating the information generally not available for catchment scale implementations (eg. soils, growth parameters and terrain analysis).

3. SUMMARY

Components of the CLASS Modelling Framework are described along with some illustrations of testing and implementation of the CLASS tools. The framework is supported by a user-friendly graphical interface. CLASS U3M-1D, PGM and CGM models and a detailed technical description of all components of the CLASS Model are available for download from the Toolkit web site (www.toolkit.net.au/class). To date there have been a total of about 430 downloads of the CLASS tools. The remaining CLASS tools – Spatial Analyst, U3M-2D and CLASS 3PG+ have been developed and tested and will be released through the Toolkit site by December 2005.

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