Using a Catchment Contour Approach for Simulation of Ground and Surface Water Behaviour Within Agent Based Modelling Platforms.

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EXTENDED ABSTRACT

Agent based modelling (ABM) environments are becoming increasingly popular for investigating the effects of land use change. The ABM environment enables models to be developed that simulate biophysical, economic and social processes at different spatial and temporal scales. The smallest spatial area modelled here is the paddock at a daily temporal resolution, therefore enabling daily interaction of the biophysical and social processes at the paddock scale. Shown here are the steps towards the development of the large scale catchment model that captures the finer spatial and temporal paddock scale processes. These steps involve deciding on the catchment area that captures the land use change to be investigated. Dividing the catchment into subcatchments and defining an appropriate number of contour segments depending on the area of the paddocks to be modelled. Paddock runoff and groundwater flow is modelled using a water balance model. Within each contour segment, runoff is summed and groundwater flow is calculated in a representative radial cross-section using a groundwater model. Contours provide an improvement to catchment modelling as the number of contours generated could also depend on the availability of model parameter data therefore simplifying the reuse of the model within other catchments.

The Recursive Porous Agent Simulation Toolkit (Repast), which is an ABM environment, is used to build the Single Entity Policy Impact Assessment (SEPIA) model. SEPIA provides a modelling platform that combines the social agents (land managers) with the biophysical agents (surface and groundwater hydrology models) and spatial agents (subcatchments, contours, paddocks, etc). The results presented here use the SEPIA model version that was established for the Bowen Broken catchment, Queensland, Australia. This version of SEPIA includes land managers for beef cattle (grazing) production. SEPIA models the social world of the Bowen Broken catchment by creating land manager beef cattle production agents and simulates their behaviour resulting in the enactment of one of a number of possible land-use strategies. The land managers make land-use decisions which in turn have effects on biophysical conditions, the level of financial payoffs associated with agricultural production and a desire to maintain or improve the state of the biophysical environment. The land manager’s decision to enact a land-use strategy is also influenced by exposure to changes in the biophysical world like sediment, cover, climate and yield variations at the finer daily temporal and paddock spatial scale. This then affects the manager’s sense of environmental wellbeing for the property.

For the purpose of this paper we use the biophysical world within SEPIA to estimate paddock scale sediment results to demonstrate the importance of finer scale modelling. If SEPIA used an annual sediment model then the outcomes may be quite different where the relationship between sediment and precipitation may be assumed more linear. Here we are able to model daily pasture growth and expose slower winter and faster summer growth patterns. The effect of slower winter growth reduces total paddock biomass and may effect cover factor depending on a number of other modelled variables (stocking rate, etc). Higher winter rainfall combined with lower cover factors or extended dry periods preceding a wet year typically drive the increase in sediment export during those years.

Although SEPIA does produce daily and annual sediment figures it is important to consider the uncertainty related to the model inputs and consequent outputs. This uncertainty is primarily driven by the lack of understanding of the biophysical processes at play and the deficiency in measured field data at required scale and frequency.

1. INTRODUCTION

Most existing ground and surface water modelling is undertaken using non-ABM or dynamic models. These models are either based on well understood reductionist science that was developed for small scale models, or empirical lumped parameter models at large scales. Although the small scale models have been developed into large scale models using discretisation of the landscape they have not been a resounding success due to heterogeneity and complexity of water flows at different space and time scales. This then results in difficulties with parameterisation and some researches, Beven et al. (2002) suggest that up-scaling in hydrology may be impossible until we have better understanding or find better ways to do this.

Agent Based Models (ABM) have evolved from a desire to model human social behaviour and individual decision making, Bonabeau (2002). ABM's for investigating the effects of government policy on land use change are becoming increasingly popular, Heckbert et al. (2005) but require the development of not only social and economic but also biophysical agents. Some of the more significant ABM environments available today include Swarm, Repast, NetLogo, AnyLogic, MASON and Ascape, Samuelson et al. (2006). We use these ABM environments to create complex models by integrating well understood scientific models at a smaller scale, then scaling up within the ABM framework. The ABM framework is then used to simulate and to also coordinate and drive the behaviour and interactions of the well understood smaller scale scientific models.

For the purpose of this paper we will consider our modelled area to be a catchment, which is then further divided into subcatchments. An appropriate number or contour segments are then defined within our subcatchments depending on the average size of the paddocks to be modelled. Paddock runoff and groundwater flow is modelled using a water balance model , Cook et al. (unpub.-b). Within each contour segment, runoff is summed and groundwater flow is calculated in a representative radial cross-section using a groundwater model, Cook et al. (unpub.-a). The open source Recursive Porous Agent Simulation Toolkit (Repast), North et al. (2006) is then used to build the Single Entity Policy Impact Assessment (SEPIA) model, Smajgl et al. (2006). The biophysical modules of SEPIA are then used here to illustrate the possible variation in outcomes relating to time and spatial scale.

2. DEFINITIONS

To ensure readers understand the meaning of the terminology used a number of definitions are provided here.

Object-oriented programming (OOP) can be conceptualised as a collection of cooperating software objects. Each object has its own state contained in variables and behaviour preformed by methods. These methods can modify the objects state or communicate with other objects by sending and receiving messages. Each object can be viewed as an independent entity within a software system with a distinct role or responsibility.

An entity describes something material or non-material that has a distinct, separate existence within the real world. The software representation of the real world entity is often referred to as an agent. Agents mimic entities by existing as autonomous software objects within agent based models (ABM) and by simulating them to model the real world behaviour of the entity.

3. METHOD

The methods presented here describe the steps that were taken to implement the contour approach for modelling the surface and groundwater hydrology within an object oriented programming (OOP) agent based modelling environment, Repast. The contour approach requires the generation of a number of spatial data files for the modelled catchment area. These spatial data files include subcatchments, contours, paddocks, reaches and pour points. The spatial data files are created using ArcGIS within the ARCGIS desktop package produced by ESRI.

An ABM is a computational model often used to create dynamic systems that simulate social agents using simple rules that often result in emerging complex behaviour. This modelling approach differs from equilibrium simulation systems where a steady state is achieved using analytical methods resulting in an unchanging system. The potential benefit therefore in using an ABM is that it allows for a complemented traditional analytical approach by exploring the way in which those equilibria are generated.

The agent based modelling environments like Repast are typically constructed using Object-oriented programming (OOP) languages like Smalltalk, Python, Java, C++ etc. Software objects are conceptually similar to real-world objects or entities; they consist of state and related behaviour.

An object stores its state in fields and exposes its behaviour through methods. Methods operate on an object's internal state and serve as the primary mechanism for object-to-object communication. An OOP ABM may be seen as a collection of cooperating agents (objects) that have their own behaviour and current state. When we build an ABM we need to think of the agents involved, their associated behaviour and their current state.

The Single Entity Policy Impact Assessment (SEPIA) model, Smajgl et al. (2006) utilises the open source Recursive Porous Agent Simulation Toolkit (Repast) to simulate land-use decision making by land managers. REPAST is a free open source toolkit that has been implemented in several languages including java and has built-in adaptive features such as genetic algorithms and regression, North et al. (2006).

SEPIA has a collection of software agents (objects) that mimic the real world behaviour of land managers for sugar cane, tree fruits (banana), and beef cattle (grazing) producers. SEPIA also incorporates the biophysical world that our land managers interact with. The land manager agent behaviour results in the enactment of one of a number of possible land-use strategies. The effect of these land-use decisions in turn has a possible effect on biophysical conditions at the paddock scale, a resulting outcome for agent financial payoffs associated with agricultural production, and a potential raised level of environmental gratification derived from the state biophysical world.

The biophysical world within SEPIA is modelled at the paddock scale using java software classes for the surface and groundwater hydrology models and spatial data files. This is achieved by linking the paddock spatial data file to a paddock agent that also instantiates the surface and groundwater hydrology classes. The paddock then executes the surface and groundwater hydrology models at a daily time step to potentially produce run-off and groundwater. The run-off and groundwater is then moved through the catchment via the contours, reaches, pour points and subcatchments.

3.1. Spatial Data Files

SEPIA is typically used to model land use change within a catchment. The catchment for a particular river system can be defined as the surface area of all land, which drains into it. Surface flows from paddocks will runoff into these river systems while groundwater flows will move via water tables. The redistribution and/or export of sediments and contaminants etc that are transported within these flow systems is of interest to the SEPIA model users. These outcomes though rely heavily on the estimation of surface and ground water flux (volumetric flow rate Q) which we have considered initially more important for achieving an ABM hydrology platform where sediment and contaminant models can be later built onto.

If for our SEPIA model we consider a catchment approach for using the surface and groundwater hydrology model then the largest spatial area would be the catchment, which we then segment into subcatchments as illustrated in Figure 1. The sub-catchment is then divided into contours with each contour having a reach and a pour point.

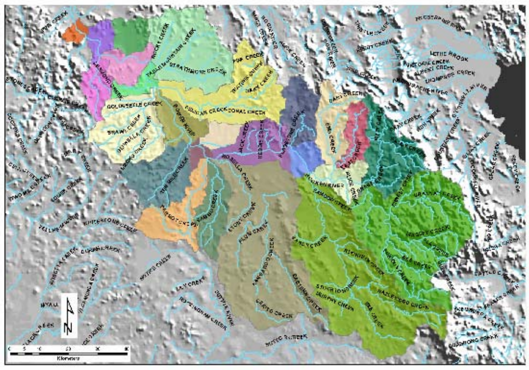

Figure 1. Subcatchments created for the Bowen Broken catchment in Queensland, Australia using ESRI ArcGIS.

The contours are the spatial entities within which the paddocks are nested in order to develop the surface water and groundwater model calculations. Depending on the spatial location and size of a paddock it may lie within more than one contour or subcatchment. We create a new shape file called “contour paddocks” that contains paddocks and partial paddocks that exist within each contour within each subcatchment. This allows us to then run the surface and groundwater models at that paddock or partial paddock scale and scale up only those paddocks or partial paddocks that exist within each contour. Although we model the hydrology at a paddock or partial paddock scale the land management is still performed at the paddock scale and is replicated where partial paddocks exist. The use of contours may provide an improvement for catchment modelling where the size of the contour is determined by the available model parameter data.

ESRI ArcGIS is used to create the subcatchments as shown in Figure 1. In Figure 2 an appropriate number of contour segments are then defined for the subcatchment. The contours are generated by first using a nearest neighbourhood smoothing algorithm that is applied to the associated digital elevation model (DEM) in order to minimise sharp angles. The smoothed DEM is then used to generate an ArcGIS shape file containing a set of contours at a specified contour interval. The contours shape file is then intersected with a shape file of the catchment boundary in order to create the contour polygons, with each polygon being assigned a homogenous elevation value taken from the adjacent contour below each polygon, i.e. each polygon is treated as a 'plateau' or step beginning at the contour line with the next 'plateau' beginning at the next contour.

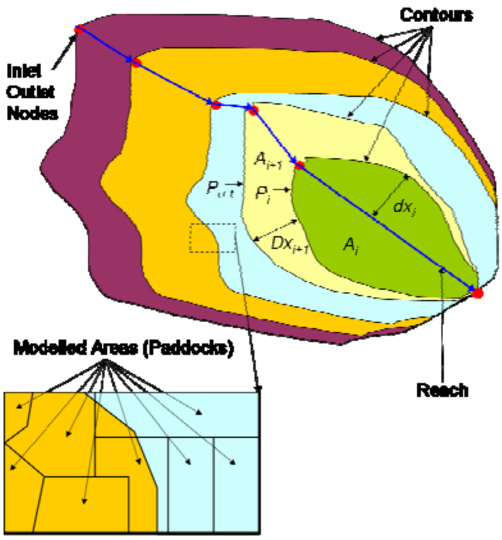

Figure 2. Subcatchment with five contour segments each with a reach, pour point and whole or partial paddocks.

The contours are then combined with the subcatchments, using a union operation within ArcGIS. The subcatchments contour shape file is then 'unioned' with the shape file containing paddocks to create the required "contour paddocks". A slope grid is created from the smoothed DEM, and a zonal attribute of average slope is extracted from the slope grid and added as an attribute for each polygon in the final "contour paddock" shapefile. Therefore, although contour polygons are treated as 'plateaus' or steps, individual contour paddocks have their own associated elevation. The number of contours required depends on the spatial size of the "contour paddocks" as each contour should have reasonable number of representative modelled areas.

3.2. Water Balance Model

The biophysical landscape within SEPIA is based on two models; the water balance model that drives the hydrology at the paddock scale and the ground water model that moves the groundwater through each contour segment.

The water balance model developed by, Cook et al. (2007b) uses a cascading bucket model with modifications to allow for improved soil evaporation. This modification follows, Deardorff (1977) and uses a force/restore method to better determine soil evaporative losses. This requires that the first layer (Figure 3.) is a surface layer nested within layer 2. Layer 1 the surface layer is required because soil evaporation is often underestimated, Deardorff (1977). Deardorff (1977) devised a force-restore model often used in heat transport modelling for soil evaporation which has been used here with some adaptation. There is a transfer of water to or from the surface layer, from or to layer 2 by an exchange coefficient. In Deardorff's model this exchange coefficient (C1) is an empirical parameter. The block arrows in Figure 3 represent material fluxes of water; $T_2,\ldots, T_n$ is transpiration from all other layers where plant roots extend into; P is the precipitation; R is the surface runoff; $Z_1,\ldots, Z_n$ is the depth of the layers; Z_x is the depth of all layers (bulk layer) and $f_1,\ldots, f_n$ is the flux between layers with flux from the final layer being deep drainage. The runoff, R in Figure 3 generated by the model at the paddock scale is then summed for each of the modelled areas that lie within the contour segment.

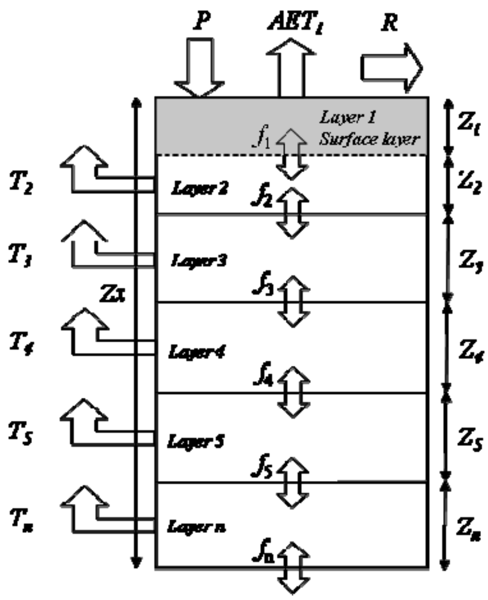

Figure 3. Schematic diagram of cascading bucket model.

Depending on available catchment data the model can run with just layer 2 and assumes the soil properties for layer 1 and 2 are the same. The model provides some flexibility by allowing the amount of catchment data and or assumptions at the paddock scale to determine number of layers used for the model.

3.3. Ground Water Model

The second model, Cook et al. (2007a) uses the contour segments created for each of the subcatchments (Figure 2.) where within each contour segment the groundwater flow is calculated in a representative radial cross-section. The areas ($A_{j,\ldots,}A_n$) and perimeters ($P_{j,\ldots,}P_n$) and average distances between successive contours ($dx_{j,\ldots,}dx_n$) are calculated using ESRI, ArcGIS. The final contour (dx_j) is the average orthogonal distance to the water course.

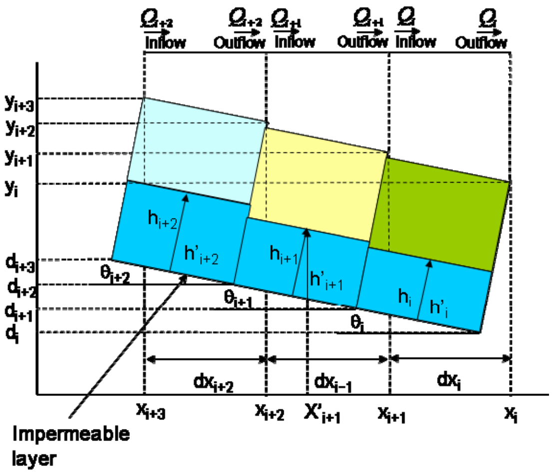

Figure 4. Groundwater model schematic for contour segments in cross-section showing the x, y and d reference planes, flux $Q_i,\ldots,Q_n$, angle $\theta_i,\ldots,\theta_n$ and vertical depth h'_i to the impermeable layer.

The angle of the surface and by assumption the impermeable layer is used to calculate $\theta_i,\ldots,\theta_n$ and allows for slope to vary between contours. The flux of water being moved between successive areas between contours is calculated down a representative radial cross-section within each contour. The depth to the water table for each paddock within the contour from the previous iteration is then used to calculate the average depth to the impermeable layer and water table depth. The flux of water between contours can be calculated by Darcy's law.

$$Q_i = -P_i h_i' K_i \left(\frac{h_i' - h_{i+1}'}{x_i' - x_{i+1}'} \right) \quad (1)$$

The vertical depth this flux occurs through is h'_i and the length is the perimeter length of the next contour P_{i+1}. The outflow volume from the area between i and $i+1$th contours into the area between the $i+1$th and $i+2$th contours is calculated using [1].

We assume here that the soil below the groundwater level is saturated so Darcy's law is applied here assuming a saturated situation where the flux rate is proportional to the gradient of the head and proportionality constant K. K at this scale is at best an empirical fitting parameter that is untestable.

The flow rate of water either added to or lost from each contour is then calculated and the average water table height is calculated for all paddocks within each of the contours. The calculation of water table height at the paddock scale will allow for future integration of solute modelling.

3.4. Agent Based Platform Integration

Repast includes classes to work with GIS shape files and their associated attribute files. There are two commonly used classes for GIS integration; the first is a data class for reading and writing from within Repast to a GIS file, the other is a display class which coordinates the display of the GIS with updates from the modelled agents. There are two main GIS systems for use with Repast, ESRI ArcMap and OpenMap. OpenMap like Repast is free and open source and to date has been the preferred GIS toolkit for SEPIA.

4. RESULTS

For the purpose of this paper we use the biophysical modules within the SEPIA model (Bowen Broken) , Smajgl et al. (2007) to illustrate some of the benefits that a surface and groundwater OOP hydrology model has when implemented within an ABM framework. ABM models are essentially OOP models, where every real world entity we simulate becomes an independent object within the model. Each independent object then has the capability to initiate their own or other objects behaviour at different time scales. To illustrate this point we examine more closely the generation of daily sediment data and expose scenarios that would not have occurred in an annual sediment model.

In SEPIA the daily paddock runoff is generated by the water balance model and becomes the primary driver for sediment transport currently implemented in the SEPIA model. The cover factor (CF) used within the SEPIA model is derived from work by, McIvor (2002) that incorporates daily biomass from the biophysical model. CF is then used in the linear shape function [2] derived from results from, Elliott et al. (2004) to calculate a sediment rate (SR) in grams per cubic metre.

$$SR = (25 * (100 - CF) + 50) \qquad [2]$$

The daily paddock runoff (RO) in millimetres and paddock area (A) are then used to estimate the total daily sediment (S) in tonnes, exported from the paddock in equation [3].

$$S = (RO / 1000 * A) * SR / 1000000 \qquad [3]$$

It is important to note that there are a number of assumptions that have been made here and that sediment estimations are used more to aide the land manager in making decisions of land use change at the paddock scale rather then as a prediction of catchment sediment discharge as shown in figure 5.

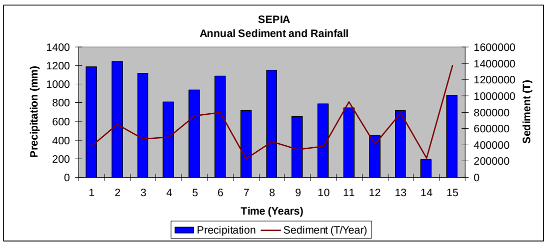

Figure 5. Accumulative annual precipitation and sediment from SEPIA for the Bowen Broken Catchment, Queensland.

The sediment figures shown in Figure 5 are derived from daily sediment estimations by SEPIA. If the sediment model used by SEPIA was an annual model then the outcomes may be quite different. In Figure 5 the relationship between sediment and precipitation is fairly linear until year eleven where a spike in sediment occurs although precipitation decreases for that year. We have plotted the daily precipitation and accumulative sediment in figure 6 to provide an explanation for this sediment spike.

Figure 6 illustrates the variation in daily rainfall from year's ten to twelve. During winter months pasture growth is slower then summer months, reducing total paddock biomass and as stocking rates remain unchanged a reduction in the CF occurs. Higher winter rainfall combined with lower CF's drive the increase in potential sediment export for year eleven. A similar pattern is observed also in year 12 and even with a reduced rainfall compared to year 10 a higher total annual sediment figure results. If an annual sediment model was used here it would use annual precipitation and may underestimate sediment during years where precipitation patterns vary from the norm. This is illustrated here where increased winter precipitation and decreased summer precipitation produce the same total annual precipitation as with a normal annual precipitation pattern but sediment results vary greatly due to the lower winter CF's. Also in Figure 5 simulated sediment loss is high in year 15 which is a result of a poor CF due to low annual rainfall and stocking rates remaining unchanged in the preceding year.

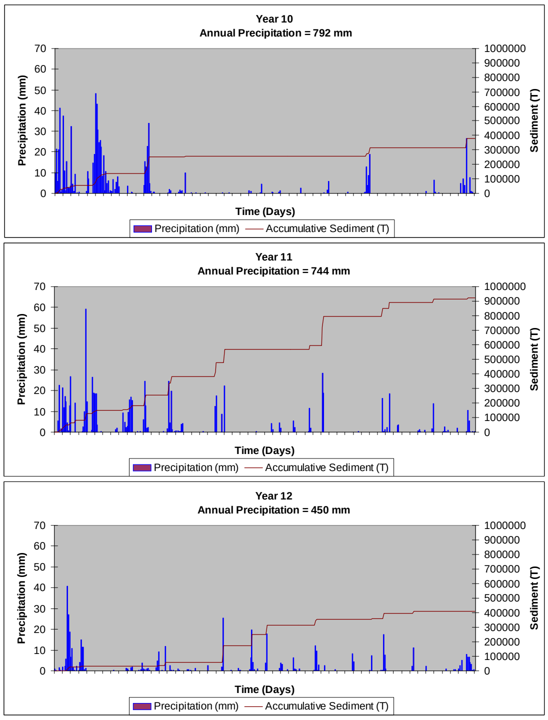

Figure 6. Results from SEPIA, Bowen Broken Catchment, Queensland, Australia comparing daily precipitation and accumulative sediment for year's ten to twelve.

The SEPIA model exposes land managers to changes in cover, climate and yield variations occurring on a daily basis. This daily data exposure is of particularly relevance to the land managers decision process on grazing areas where ground cover can vary significantly between properties and between years, Bartley et al. (2004). The way in which land is managed can affect the cover factor and ultimately the sediment export.

Although SEPIA does produce an annual sediment figure it is important to also take into consideration the uncertainty related to the model inputs and consequent outputs. This uncertainty, driven by the lack of understanding of the biophysical processes at play and the deficiency in measured field data will hopefully improve with future work into these areas. The benefit of the SEPIA model is that its object oriented architecture will allow for easy integration of model improvements into the future.

5. CONCLUSION

The results presented in this paper use the version of the SEPIA model that was established for the Bowen Broken catchment, Queensland, Australia. By using the REPAST ABM environment, SEPIA provides a platform that combines the social agents (landmanagers) with the biophysical agents (surface and groundwater hydrology) and spatial agents (subcatchments, contours, paddocks, etc). This integration allows agents within the SEPIA to communicate at various time and spatial scales. This allows for example a land manager agent to alter his behaviour and possible land-use strategies daily.

SEPIA has the ability to drive agent interaction and model processes at different time and spatial scales and this simplifies the reuse of SEPIA in other catchments where available model parameter data can then define the spatial and temporal scale of the model. By using the biophysical world within SEPIA to estimate paddock scale sediment we also illustrate here that significant variations in estimated sediment results can also occur depending on the temporal resolution of the model and that these variations can be significant.

6. ACKNOWLEDGEMENTS

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