GEM: Spatially Distributed Dynamic Models

Objectives:

This practical has the following objectives:

1. To develop understanding of dynamic spatial models
2. to develop understanding of how GIS can be used to solve practical problems (in this case in climatology and soil science)

Scenario:

The Problem: Understanding tropical rainforests and climate

Understanding how tropical rainforests contribute to the global carbon cycle is crucial to climate change modelling. Over the years, climatologists and ecologists have sought to understand the fluxes of carbon moving between the soil, biomass and into the atmosphere as carbon dioxide. Recently, ecologists have suggested that carbon dioxide fluxes from drought-stressed tropical rainforests may be much greater than those from tropical rainforests that are not drought-stressed.

Soil water deficit is commonly used as a measure of drought stress. Unfortunately, virtually no meteorological stations in the tropics measure soil moisture directly. However, there are many meteorological stations that measure precipitation in the tropics. Is it possible that we can map changing patterns of soil water deficit using information about precipitation?

The Model:

Researchers have investigated the relationship between soil water deficit and climate in the field. From their research, it appears that the soil water deficit in the Amazon basin can be approximately estimated as follows (Malhi and Wright, 2004):

$$\text{Soil Water Deficit}_{(t)} = 0.8466 * (0.8188 * \text{Soil Water Deficit}_{(t-1)} - \text{Precipitation}_{(t)} + 118)$$

Soil water deficit can only be a positive number, so any time that this equation produces a negative number (e.g. when precipitation is very high), the soil water deficit is reset to zero.

Notice that Soil Water Deficit appears twice in this model: once on the left-hand side and once on the right-hand side. The subscripts (e.g. Soil Water $\text{Deficit}_{(t)}$ and Soil Water $\text{Deficit}_{(t-1)}$) tell us which time period we're talking about. Soil Water $\text{Deficit}_{(t)}$ means 'soil water deficit this period', whilst Soil Water $\text{Deficit}_{(t-1)}$ means 'soil water deficit last period'. In other words, this equation suggests that soil water deficit **this month** depends on soil water deficit **last month**.

The Data:

The following map layers are available:

- **prec**: There are 36 different precipitation maps, representing long-term average monthly precipitation in mm for 1996-98. Each month is indicated by the final digit or two of the name, e.g. **prec_01** = precipitation in January, 1996**, prec_02** = precipitation in February, 1996**, prec_03**, = precipitation in March 1996 etc. until **prec_36** = precipitation in December 1998. We will use just the first three grids here.

<u>Notes</u>:

(1) The precipitation data are derived from the CRU TS 2.0 global data set (New et al., 2002; New et al., 2000).

GIS Practical:

Import and inspect your data

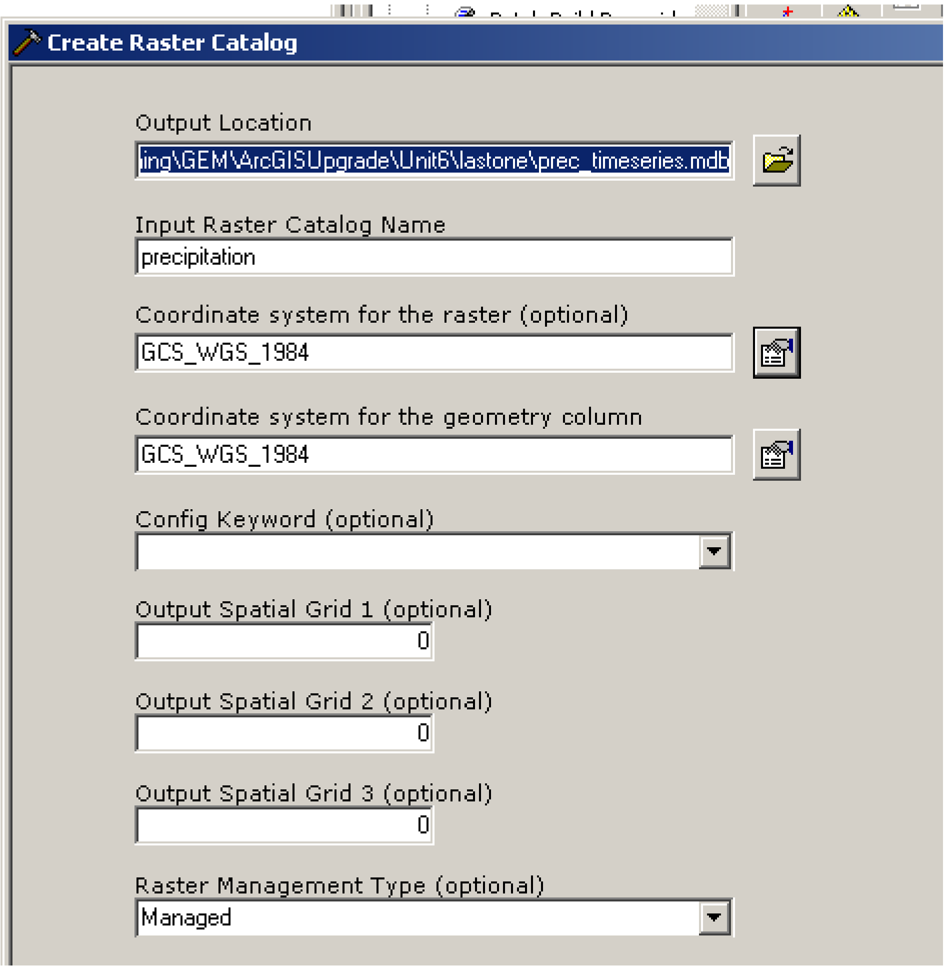
Begin by using *conversion tools / to raster / float to raster* to import the first three raster precipitation grids (**prec_01, prec_02 and prec_03**). Call the raster grids that you create **prec1, prec2**, and **prec3.**

Representing time in ArcView: raster catalogs

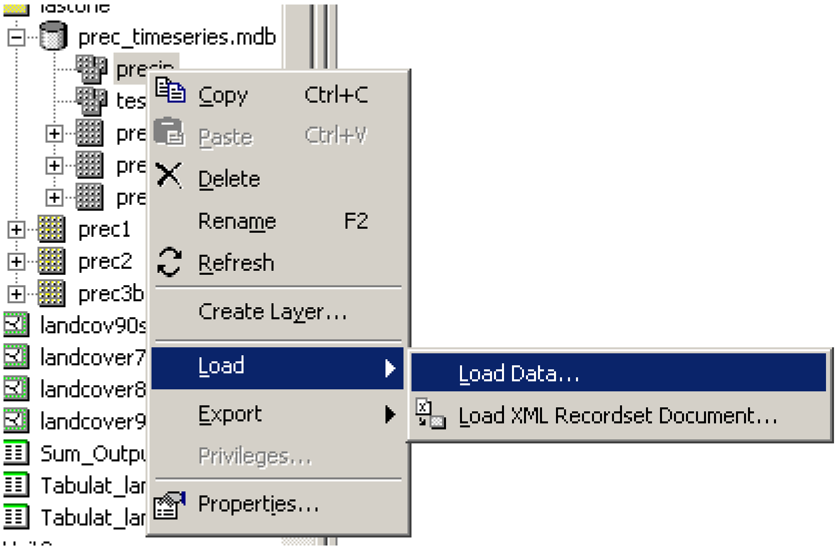
In ArcView, it is possible to store raster grids that represent **time series** data (a 'stack' of raster grids showing data for different periods), so that they can be displayed as a movie. To do this, we must store the raster grids for each different month in the same raster catalog (a raster catalog being a collection of different raster grids). We can create a raster catalog with our time series data as follows:

- In the ArcToolBox, under *Data management / workspace*, select *Create personal geodatabase.* Use this tool to create a new personal geodatabase called **timeseries** in your working folder for this exercise.

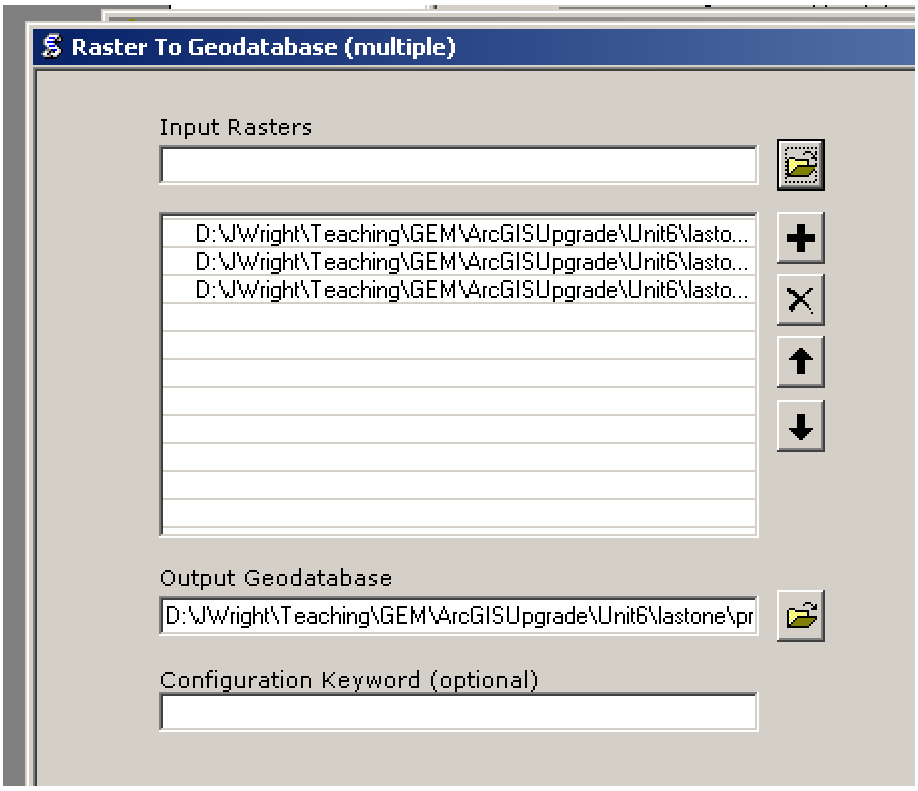
- Next, go to *data management* in the ArcToolBox once again, and choose *raster*, then *create raster catalog*. Choose your **timeseries** personal geodatabase as the *output location* (by clicking on it once only). Call the *input raster catalog name* **precipitation.**
- Under both *coordinate system for the raster* and *coordinate system for the geometry column*, click on the button to the right of these options, and then choose *select*. Under *geographic coordinate systems* and within the *world* folder, select *WGS 1984.prj.*
- Leave the remaining options as they are and hit *OK*.



- Now we need to load up our raster grids into this new raster catalog. To do this, we need to start up ArcCatalog. Within ArcCatalog, navigate to your new raster catalog in the left-hand panel of the screen, and then right-click on it. From the pop-up menu that appears, select *load*, and then *load data...*



- In the resulting dialog box, load up each of your three raster grids in order as *input rasters*, starting with **prec1** and then hit *OK*.



- Now return to ArcMap and open up your new raster catalog using *add data* on the *file* menu (or the plus icon)
- Right-click on your raster catalog **precipitation** and choose *properties*, and then click on the *display* tab.
- If you tick the box next to *redraw whole display after each raster redraw* and enter in a *delay draw* of (say) **2000** milliseconds, and then click *ok*, you should find that ArcView will cycle through the three precipitation grids, drawing each one in turn.

Raster catalogs are a useful display facility, but unfortunately, when it comes to building a model, as yet ModelBuilder and most of the tools in the ArcToolBox do not really make use of this data format.

So far, it is likely that any models that you have designed in ArcView have been static. They have considered a single period of time and have not taken account of changes in climate, policy, or vegetation, for example.

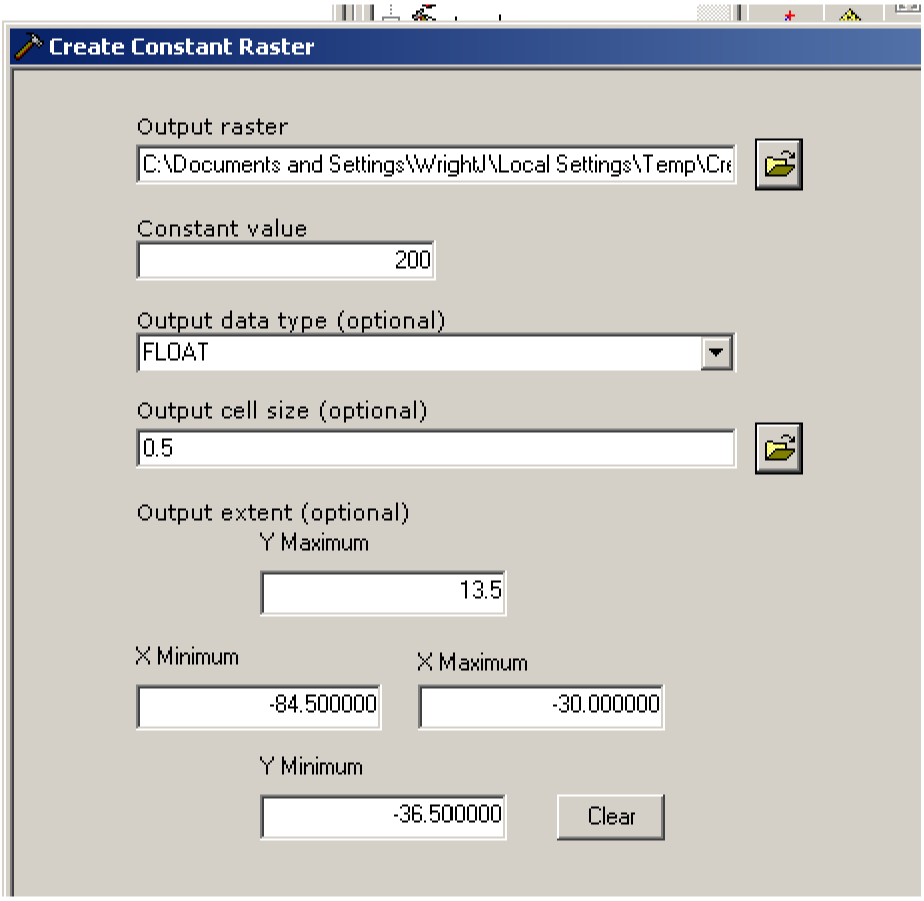
It is, however, possible for us to make our models **dynamic** and include time within them. We will now attempt this with the soil water deficit model described above.

Create a map for the start of the time series

To start off our time series, we need to set the soil water deficit to an initial level. Our data start at January 1996, so we need to create a grid depicting the soil water deficit as at December 1995 to 'get the ball rolling'. For simplicity, we'll assume that the whole of Amazonia starts off with an initial soil water deficit of 200mm.

To create this initial soil water deficit map layer:

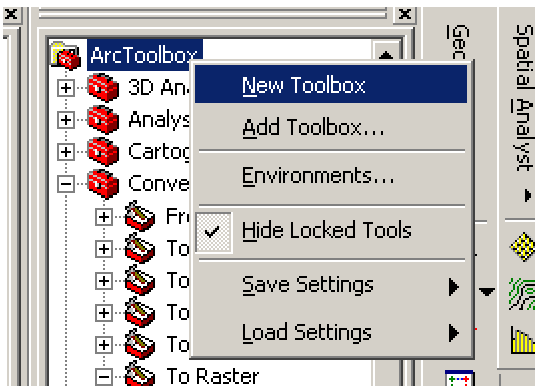
- within the ArcToolBox, select *spatial analyst tools*, then *raster creation* and *create constant raster*
- Create a new raster grid called **initial_water** with the parameters shown in the screenshot below. In the screenshot below, the *output cell size* of 0.5 and the *X and Y minimum and maximum* values have been chosen to match those of our precipitation grids. The X coordinates are all negative, because the represent degrees of longitude west of Greenwich – degrees west and south are normally negative numbers. The minimum Y coordinate is negative and the maximum positive, because our study area straddles the Equator. The *constant value* of **200** represents the initial soil water deficit of 200 mm. When you are done, click on OK.



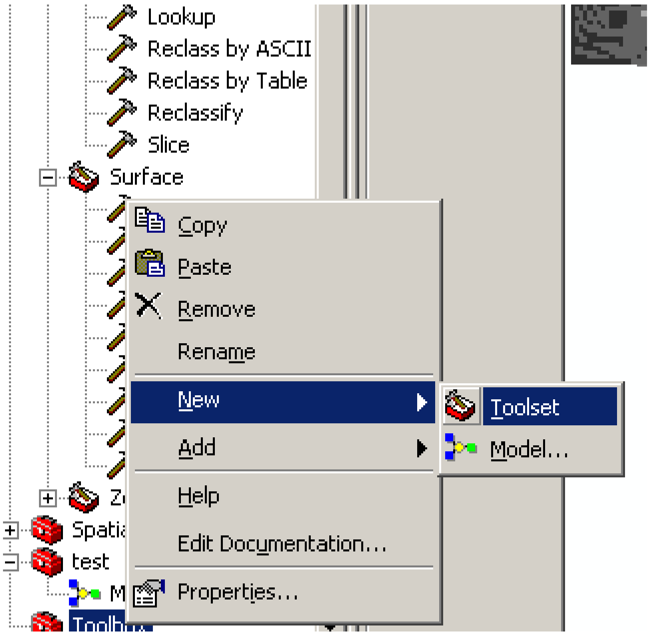
Design a dynamic model using Model Builder

Now that we have created this initial grid, we can start to build up a model of soil water deficit. To do this, we will use the Model Builder facility in ArcView:

- right-click on the ArcToolBox and choose *new toolbox* from the menu that pops up.



- You should now find that you have a new tool (called simply 'toolbox') if you scroll down to the bottom of the ArcToolBox window. You can click once on the name of this tool and rename it to something more sensible, such as 'water_deficit'.



- Right-click on your new 'water_deficit' tool and another pop-up menu will appear.
- Click on the *new* option and then select *model…*
- This will open up the ArcView Model Builder – a graphical tool for designing analytical operations. Model Builder in effect has an 'empty canvas', onto which we can add the names of map layers or ArcView tools

Task 1:

Now that we have a space in which to create a model, look back at the equation on page 1. See if you can create a model in ModelBuilder that implements this equation, using **initial_water** as Soil Water Deficit$_{(t-1)}$ and **prec1** as Precipitation$_{(t)}$.

If you are unsure, a suggested approach is given on the following pages.

Solution to task one:

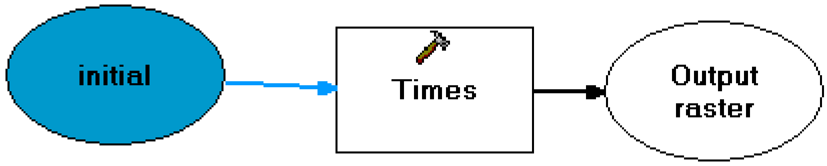
We're going to start by doing the bit of the equation shown in bold and underlined:

Soil Water Deficit$_{(t)}$ = 0.8466 * (**0.8188 * Soil Water Deficit$_{(t-1)}$** – Precipitation$_{(t)}$ + 118)

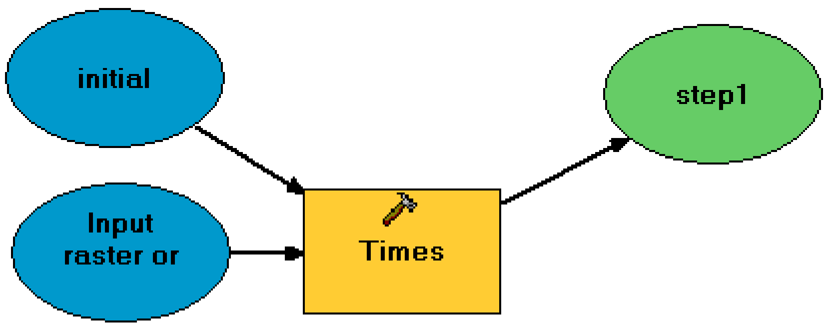
- drag and drop the **initial_water** map layer into the Model Builder window from the list of map layers on the left of your screen.

- Next, we need to multiply this by 0.8188. Drag and drop the *times* tool into the Model Builder window (this under *spatial analyst tools / math*).

- Click on the connector tool (shown above) and then click once inside the **initial_water** oval and once inside the **times** box to make **initial_water** an input to our *times* calculation.
- Double-click on the *output raster* and change its name to **step1**.



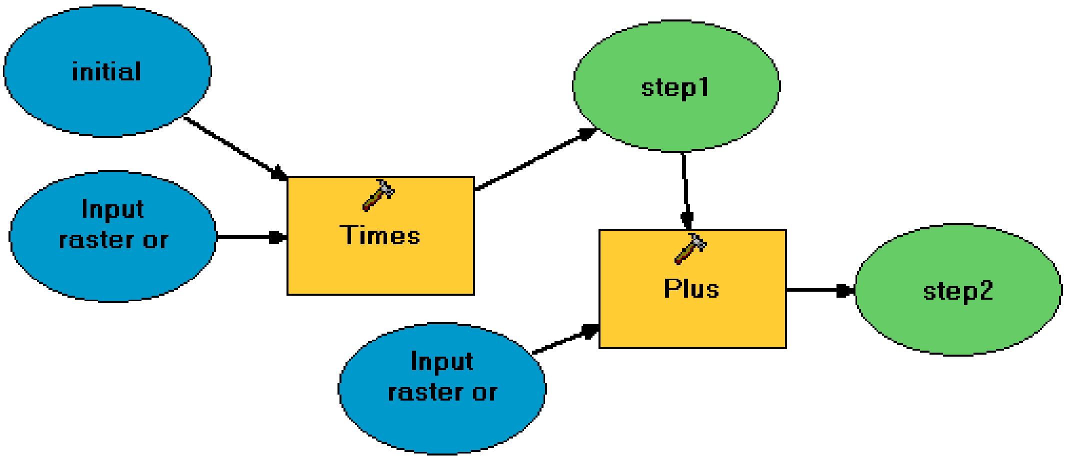
- finally, double-click on the *times* box and type in **0.8188** next to *input raster or constant 2*.
- Your diagram should now look something like this (you may need to move the symbols around slightly to tidy it up):



Now for the next bit – the + 118 part underlined:

Soil Water Deficit$_{(t)}$ = 0.8466 * (**0.8188 * Soil Water Deficit$_{(t-1)}$** – Precipitation$_{(t)}$ + **<u>118</u>**)

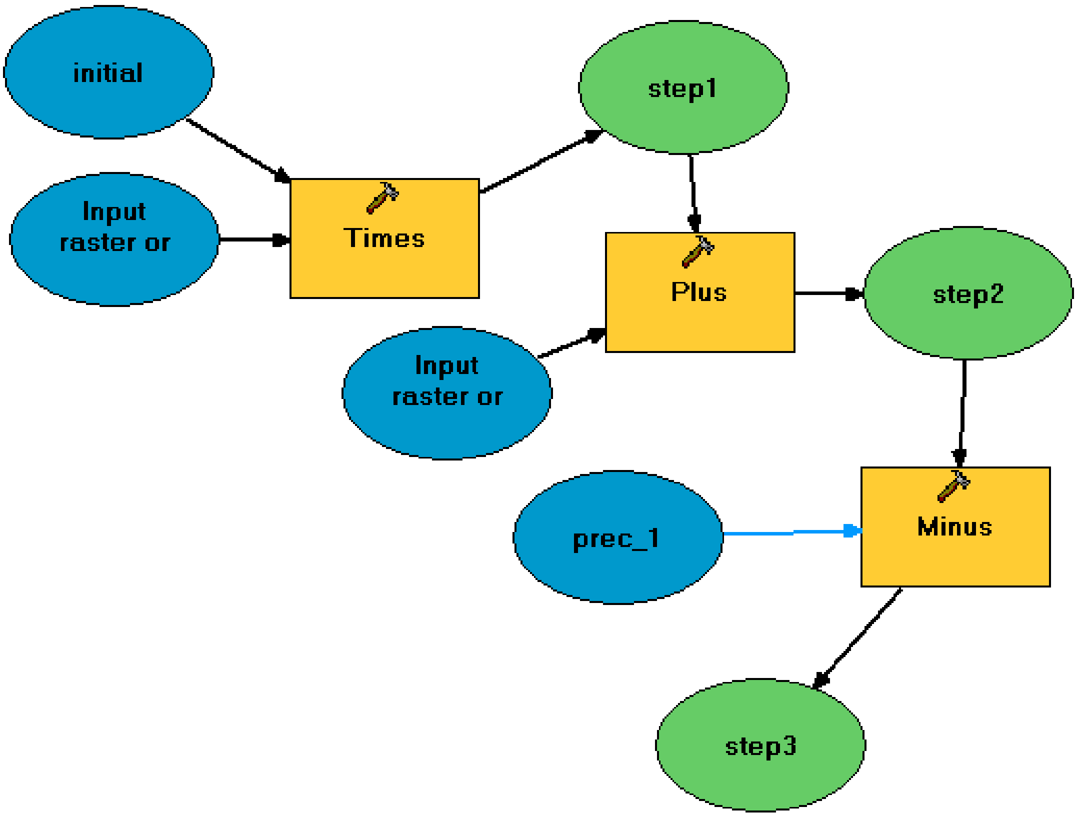
- Drag and drop the *plus* tool from within *spatial analyst tools / math* into the Model Builder window.
- Draw a line linking this to the **step1** oval. Call the *output raster* from your plus operation **step2**. Double-click on the *plus* box and set the *input raster or constant 2* to **118**.



Now we need to calculate the precipitation part (underlined):

Soil Water Deficit$_{(t)}$ = 0.8466 * (**0.8188 * Soil Water Deficit$_{(t-1)}$ - Precipitation$_{(t)}$ + 118**)

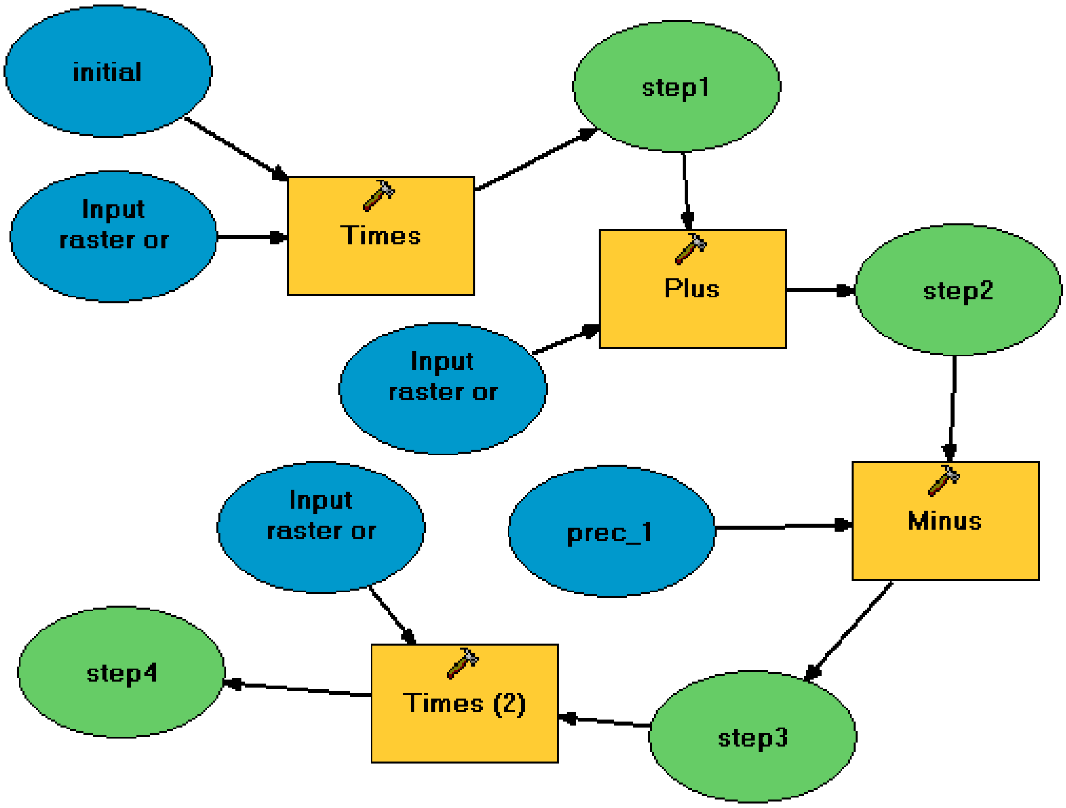
- drag and drop the **prec1** grid into your ModelBuilder window.
- Drag and drop the *minus* tool from within *spatial analyst tools / math* into the Model Builder window.
- Draw a line from **step2** to the *minus* box and then from **prec1** to the *minus* box. If you double-click on the *minus* box, you should now find that ArcView will subtract the precipitation grid from the results of our calculation so far (in **step2**).
- Change the name of the *output raster* to **step3**. Your model should now look like the diagram below:



We've now done all of the parts of the equation shown in bold. We simply need to do the final part, multiplying the result of our calculation so far by 0.8466:

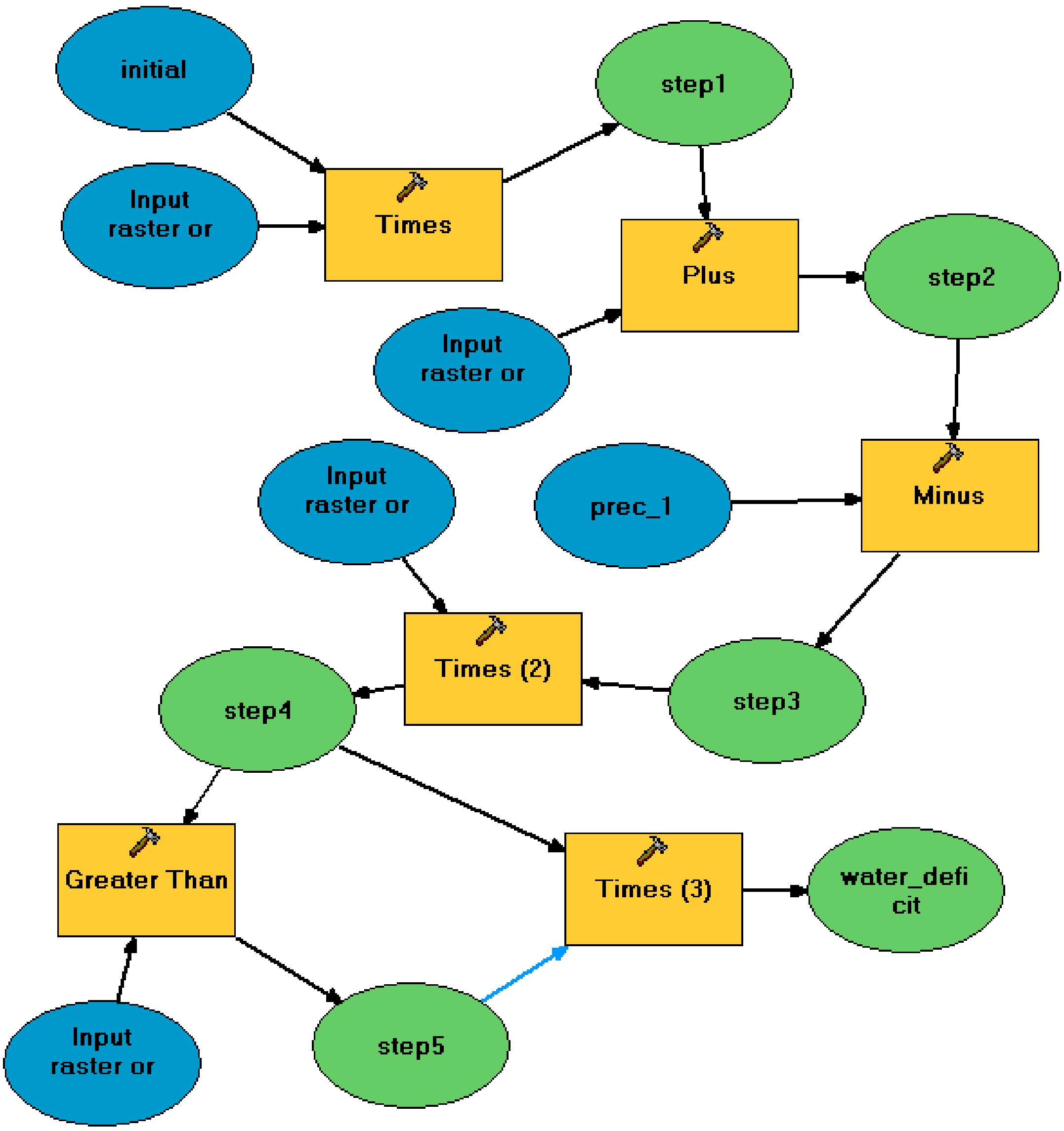
Soil Water Deficit$_{(t)}$ = 0.8466 * (**0.8188 * Soil Water Deficit$_{(t-1)}$ - Precipitation$_{(t)}$ + 118**)

- to do this, drag and drop the *times* tool into the Model Builder window once again.
- Draw a line from **step3** into this tool.
- Double-click on the output raster again and call it **step4**.
- Double-click on the *times (2)* box, and set the *input raster or constant 2* to 0.8466. Your model should now look something like this:



We still have one more job to do. If you re-read the model description on page 1, you will notice that our model can only take positive numbers (a positive soil water deficit number means that our soil water column is saturated and has water sitting on top of it). We therefore need to reset any negative numbers to be zero. To do this:

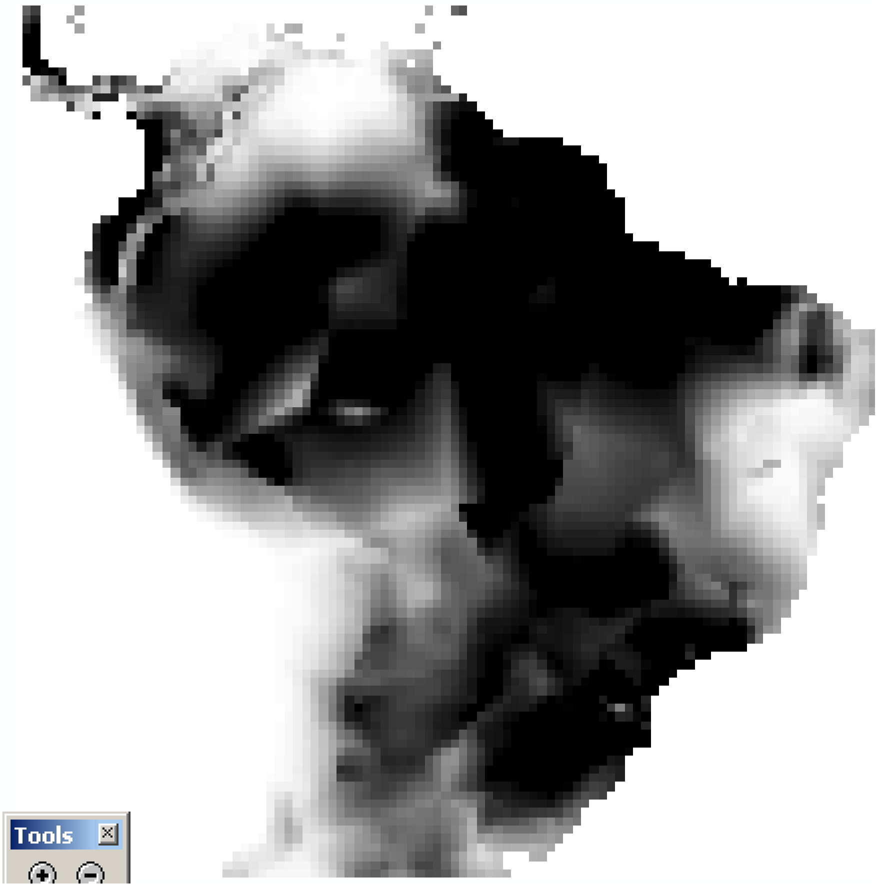
- Within *spatial analyst tools / math*, double-click on *logical* and drag and drop the *greater than* tool into your Model Builder window.
- Draw a line from the **step4** oval to the *greater than* box. Double-click on the *output raster* again and call it **step5**.
- Double-click on the *greater than* box and set the *input raster or constant 2* to be **0**.
- Finally, drag and drop the *times* tool from within *spatial analyst tools / math* into your Model Builder window.
- Draw lines linking this *times* box to **step4** and **step5**. Double-click on the *output raster* once more and call it **water_deficit**.
- Hopefully, you should now have a formidable-looking model like the diagram below, which you should now save (via *save* on the *model* menu).



Run your model:

Try running your model and see what happens. You can do this by clicking on the *run* button:

Close down your model window, being sure to save your model first. Take a look at the output raster grid, **water_deficit**, and see how it looks. You should find that it looks something like the screenshot below:

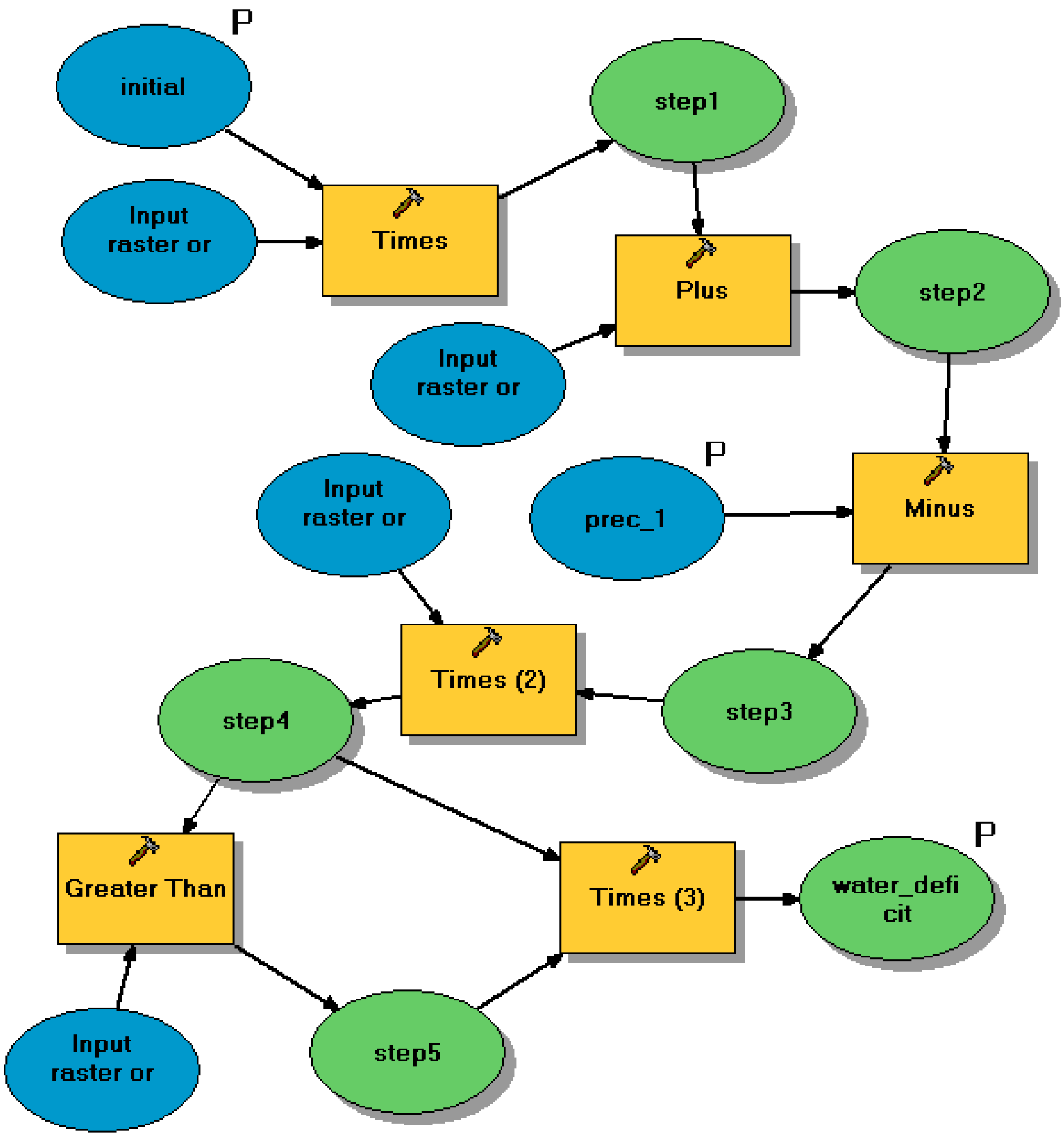


Parts of the Brazilian coast, Venezuela, and the western coast along Peru and Chile are running up large soil water deficits and appear in lighter colours.

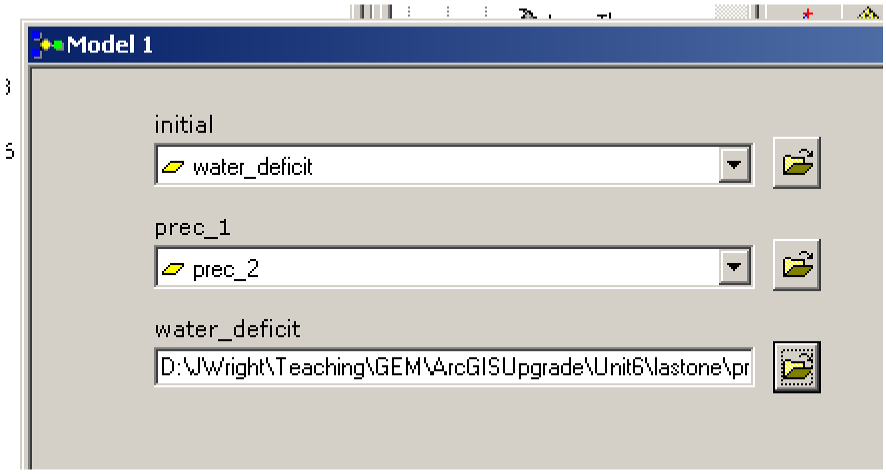
Running the model for different time periods:

So far, we have run our model for the first month (January 1996) in our set of 3 months of precipitation data. We can, however, run it for the remaining two months (February and March 1996) as well. To do this:

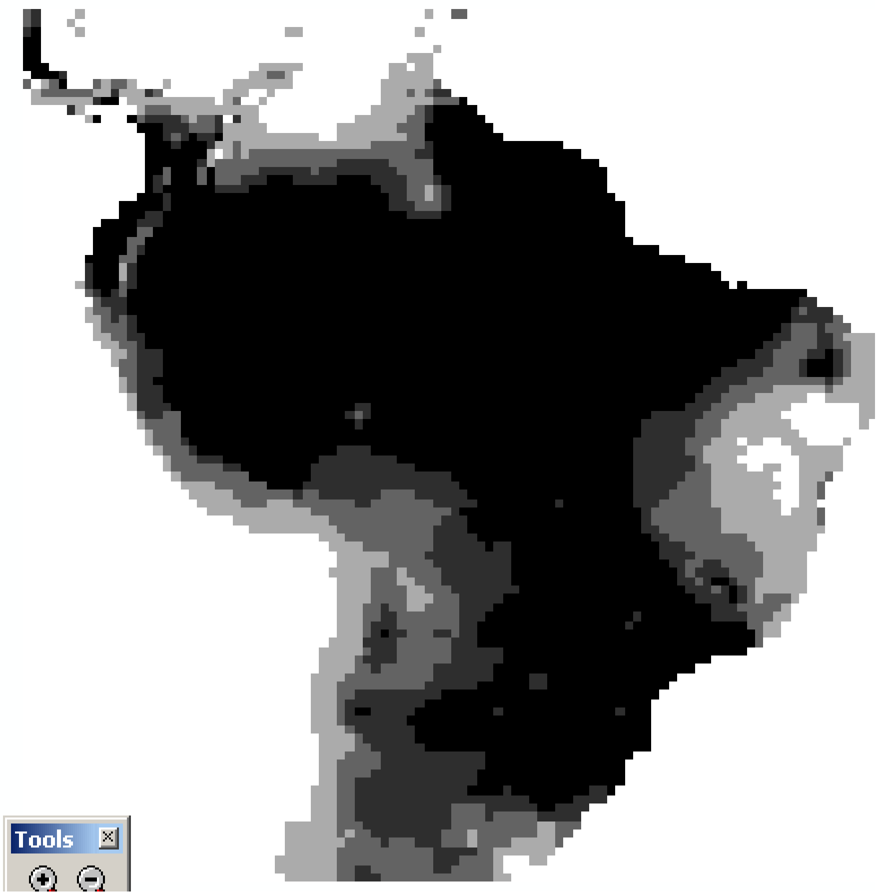
- right-click on your new model tool in the ArcToolBox, and then choose *edit* from the pop-up menu that appears.
- Right-click on the initial_water oval and in the pop-up box that appears, select *model parameter*.
- Do the same for both **prec1** and **water_deficit** to make these model parameters too. You should now see a 'P' for 'parameter' appear next to each of these 3 boxes:



- Save your model and then close the Model Builder window.
- Now try double-clicking on your new model tool in the toolbox. This time, you will be prompted to enter the locations of all the raster grids that you set as parameters.
- What we can now do is to feed in our results from the first month into the next month's calculations. To do this:
    - Set the starting raster grid of soil water deficit to be **water_deficit**. In effect, we are feeding in the soil water deficit that we calculated from last time around into the next month's calculations here.
    - Set the precipitation raster grid to be **prec2**. Here, we are now feeding in the next month's precipitation figures.
    - Set the output *water deficit* grid to be **water_def2** – we will use a different name for the output, because it represents a different month's soil water deficit.



- We can now run this model by hitting OK, but this time it will be for the next month in the time series – February 1996.
- Take a look at your **water_def2** map layer (you may need to display this using a *classified* symbology) – it should look something like this:



Again, the lighter areas are in eastern Brazil, where soil water deficit is high.

Try running the model one more time using the next month's precipitation data:

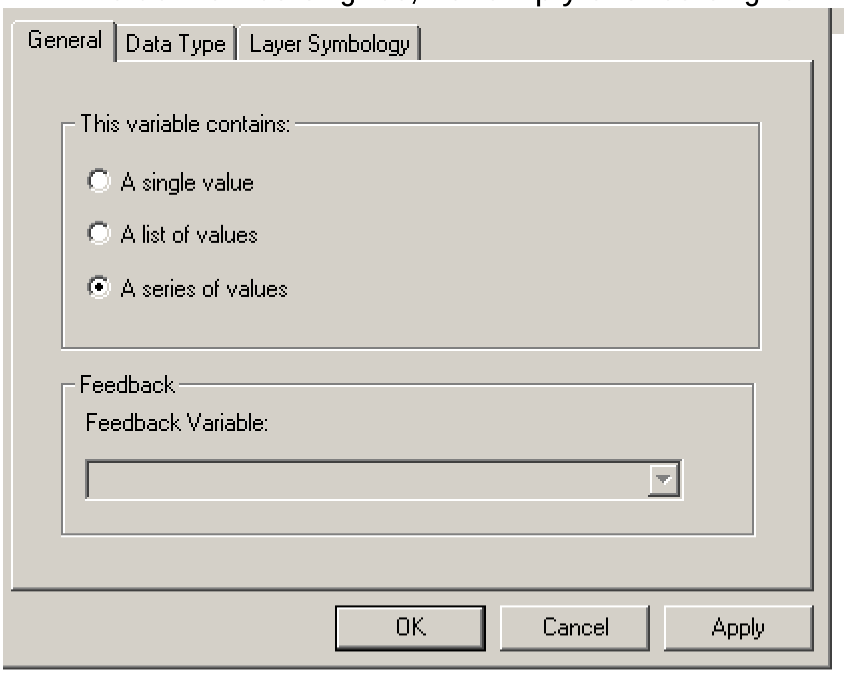
- Double-click on your new model tool in the toolbox once again:
    - Set the starting raster grid of soil water deficit to be **water_def2**.
    - Set the precipitation raster grid to be **prec3**. Here, we are now feeding in the next month's precipitation figures.
    - Set the output *water deficit* grid to be **water_def3**.
    - Run the model again.

We have run our model once again, but this time for March 1996. We could carry on in this way, running the model again and again for the rest of the months in our time series.

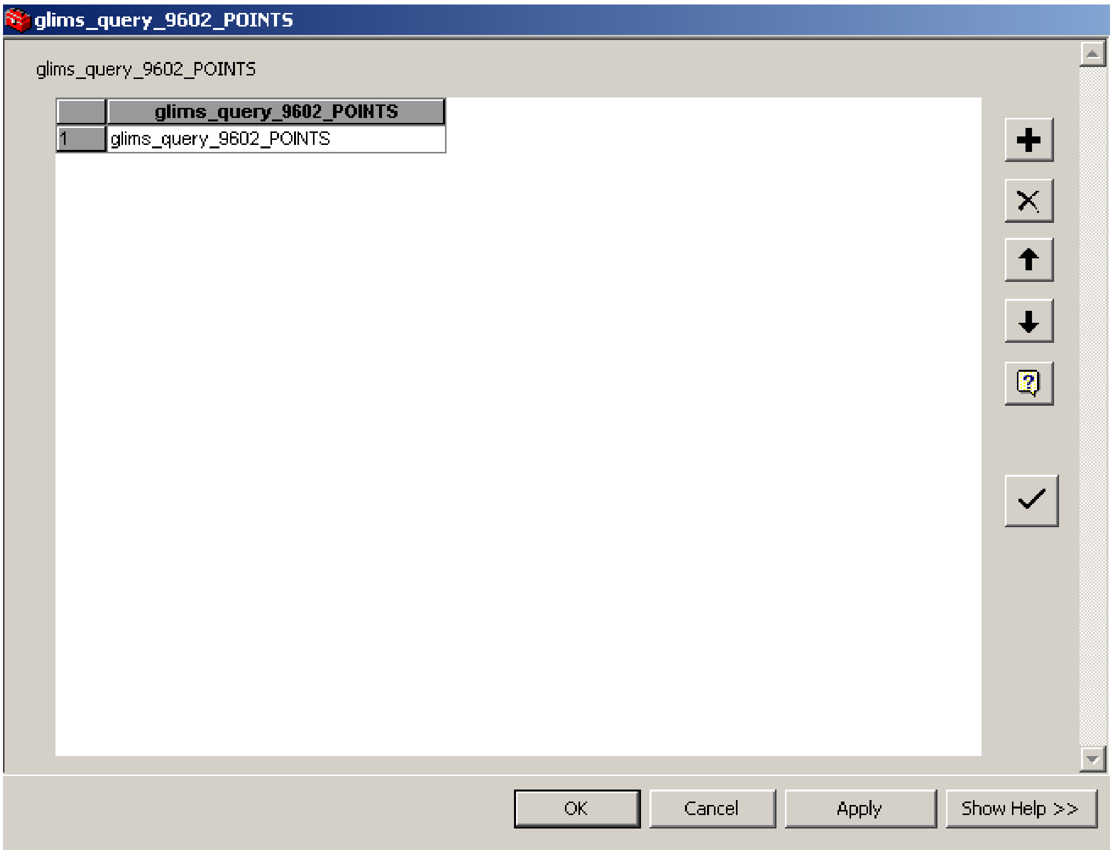
Ideas for taking this practical further (optional – ArcGIS 9):

There are other ways of building models over time using the Model Builder feature within ArcGIS. In particular, you can have your model run on a time series 'stack' of raster grids, rather than entering in the relevant month's data at each time step:

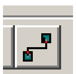
- Right-click on your precipitation raster grid within your model and uncheck the 'model parameter' option on the pop-up menu. Do the same for the **initial** map layer too, so that this is no longer a 'model parameter'.
- Right-click again on your precipitation raster grid and this time select *properties* from the pop-up menu.
- Select *a series of values* from the *general* tab on the properties dialog box and click OK. This will enable the model to run with a 'stack' of raster grids, not simply one raster grid.



- Click on *OK* and note how the symbol for precipitation now changes to be a 'stack' of map layers. Double-click on this modified symbol for precipitation and you can enter in the names of each month's raster layers in sequence. Use the '+' button on the right of this dialog box to add further layers to the list, the X to delete any rows you inadvertently create within this grid, and the ↑ and ↓ buttons to alter the order of the months in the sequence. Click OK when you have entered in the names of a number of months' worth of data files.



- You can now also set up what is known as a 'feedback variable', making the output soil water deficit from one model time-step the starting point for the next time-step. One way of doing this is to draw a link between your final **water_deficit** output and the **initial** map layer that forms the input to the next model time-step using the tool below.



- Another way of doing this is to right click on the **initial_water** map layer and then choose *properties* and then *feedback variable* under the *general* tab. If you select **water_deficit** here, this should mean that output values for soil water deficit from one time period form the input **initial_water** values as the model moves on to the next time period.

This functionality provides a much more sophisticated way of handling time within the Model Builder environment. Note that there are other programming constructs that can be used within the Model Builder environment too, such as ‘branching’ (where a part of a model is only processed if certain initial conditions are met).

References:

You do not have to read any of these references, but you may find them useful background.

The equation that predicts soil water deficit in the Amazon basin is taken from this paper:

Malhi Y and Wright JA (2004): ‘Spatial patterns and recent trends in the climate of tropical forest regions’. *Philosophical Transactions of the Royal Society, Series B – Biological Science* **359**: 311-329

The climate data that are used in this exercise were created by the University of East Anglia Climate Research Unit. Details of how these maps were created are available in:

New, M., Hulme, M. and Jones, P.D., (2000): ‘Representing twentieth century space-time climate variability. Part 2: development of 1901-96 monthly grids of terrestrial surface climate’. *Journal of Climate* **13**: 2217-2238