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# Predicting runoff and phosphorus loads from variable source areas A terrain-based spatial modelling approach

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## Abstract

Research has been conducted at Flaxley Agricultural Centre in South Australia to predict phosphorus loss in surface runoff from dairy pastures. Part of the research investigated if the topography based, spatially distributed hydrological model - TOPMODEL could be adapted to successfully predict phosphorus loads off dryland and irrigated catchments, where variable source area hydrology is considered a dominant process. This was carried out by integrating one season of field measured runoff and P load data with rainfall and evapotranspiration data. The methodology uses TOPMODEL to simulate runoff volume and spatial extent of saturated areas, using a topographic index - ln(As/tanB) to distribute variable source areas across catchments, within a loose coupled GIS framework. Using the simulations of runoff from the dryland and irrigated catchments, phosphorus loads in surface runoff were then simulated, using an empirically established, terrain-based phosphorus load index relatable to variable source runoff (TOPMODEL-PLI).

TOPMODEL was found to model runoff for dryland and irrigated catchments with some success, based upon one season of monitoring data. The dynamics of runoff events were reasonably accurately predicted. There was a tendency for TOPMODEL to over predict runoff volumes from catchments with a high average topographic index and under predict runoff volumes from catchments with a low average index. Results of modelling P loads using TOPMODEL-PLI for dryland and irrigated catchments were encouraging but the model tended to over estimate total P loads volumes off all catchments. A case assessment of the predicted P loads for one dryland and one irrigated catchment showed they were well within acceptable error limits. The modelled P load results may, in part be due to the accuracy of the load index that was used in TOPMODEL. Two issues are identified - the interpolation of soil P surfaces and robustness of the soil P-runoff P relationship used to establish the load index. TOPMODEL-PLI performance for catchments at FAC is encouraging. Although the prediction of P load was within acceptable error it may be improved by further research into the soil P:runoff P relationship which underpins the phosphorus load index.

**Keywords**: TOPMODEL, Hydrological modelling, terrain analysis, surface water, phosphorus

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## Introduction

The characterisation of phosphorus sources and the processes responsible for transporting of phosphorus to surface and groundwater systems are important considerations for reducing water quality problems associated with intensive agricultural practices. Any improved management plan should include the identification of regions where practices for reducing phosphorus transport will be more effective and result in a greater reduction of surface and groundwater contamination. Much research has been carried out in trying to understand the mechanisms by which phosphorus transfer in runoff occurs from intensive pasture systems and is summarised well by Dougherty et al. (2004). What is less well studied is the spatial variability associated with phosphorus runoff from pastures and whether it relates to the concept of variable source areas in terms of increased contribution of phosphorus to surface waters. This gap in knowledge and understanding is only now being addressed (Davies et al., 2005; Scanlon et al., 2005; Gérard-Marchant et al., 2006; Hively et al., 2006). The aims of this study were to determine if a spatially distributed hydrological model can:

- simulate field measured runoff, and predict variable source areas which contribute runoff from two dryland catchments and three pivot irrigated catchment at Flaxley Agricultural Centre,
- be adapted to simulate phosphorus loads off these catchments, by integrating field measurements and with empirical relationships derived from rainfall simulations.

In the concept of variable source areas (Dunne and Black, 1970), streamflow during high-flow conditions is generated where the water table rises and saturates land-surface areas. The water table rises because precipitation infiltrates into the soil, moves vertically to the saturated subsurface zone and then down slope. This is consistent with observed spatial distributions of soil moisture and potentiometric surfaces (e.g. Anderson and Burt, 1985). Variable source area (VSA) flow is thought to be an important streamflow-generation mechanism where infiltration rates are greater than precipitation rates (saturation excess runoff; for example, in undisturbed vegetated areas in humid, temperate regions). This is in contrast to the situation where infiltration excess runoff is the dominant generation mechanism (rainfall intensity exceeding soil infiltration capacity; Horton, 1933). Saturation excess runoff is dependent on the topography of the area and on local hydrodynamic, more so than on the rainfall intensity (Hewlett and Hibbert, 1967). In the focus area for this study, saturation excess runoff is the dominant streamflow generation mechanism. As such, a distributed hydrological modelling approach was considered, which would effectively characterise overland flow from spatially and temporally varying source areas.

TOPMODEL (Beven and Kirkby, 1979) was chosen as the model for this study as it provides one of the few easy to use model structures that can make use of digital elevation model (DEM) data. It is a spatially distributed, hydrologic model that predicts the spatial distribution of variable source areas based on a topographically defined wetness index, ln(As/tanB) where ln is the natural logarithm, As is the upslope contributing area per surface grid cell and tanB is the surface slope gradient. It simulates hydrological processes in a relatively simple way, particularly the dynamics of surface or subsurface contributing areas (i.e. variable source area). It also simulates the frequency distribution for the various components of the hillslope hydrology, many of which are relevant to sediment and solute transport rates. Beven et al. (1995) have reviewed the evidence for the success of TOPMODEL in predicting patterns of saturation in a number of different studies, with results suggesting it is a reasonable predictor. The overall success of the model has also been noted by Anderson et al. (1997). A number of other modelling structures were explored but were discounted, either because of excessive paramaterisation (TOPOG; O'Loughlin, 1986), inflexibility in adaptation (Macaque; Watson et al., 1998) or unsuitability at the scale of this study (THALES; Grayson et al., 1995).

## Catchment characteristics

Flaxley Agricultural Centre (FAC) is located in the Adelaide Hills, 45 km south east of Adelaide at an elevation of 400 m. The climate is Mediterranean with a mean annual rainfall of 800 mm and a mean annual evaporation of 1300 mm (Jeffrey et al., 2001). The generalised topography consists of valley floors surrounded by rolling hills. Catchments at FAC drain to the Bremer catchment system. Soils are acidic podsolics, grey sandy loam over heavy red or yellow clay sub-soils, with ironstone being present, on higher ground. Land cover is essentially phalaris, subterranean clover and perennial ryegrass pastures.

The focus for this study are five catchments at FAC, two under dryland management and three under irrigated management. The dairy pasture across these catchments has traditionally been subjected to high stocking densities. As such they provide ideal conditions to study the processes responsible for transporting nutrients to surface and groundwater systems. The dryland catchments were established and instrumented several years ago, with data collection commencing in 1996 (Fleming and Cox, 1998; Fleming and Cox, 2001). The irrigated catchments, although previously established were instrumented in 2003 for data collection commencing in 2004 (Fleming et al., 2003).

The two dryland catchments investigated in this study are designated Flaxley West and Flaxley East, in keeping with previous studies (e.g. Fleming and Cox, 1998; Fleming et al., 2001) and are 2.2 ha and 2.5 ha in area respectively (Figure 1). They have been defined by imposing an engineered barrier to the natural topography of the landscape, through the use of exclusion drains cut into the subsoil clay (Fleming and Cox, 2001). These catchments have been monitored for water runoff and phosphorus loads from 1996 - 2000 and again in 2004, by an instrumented flume at the bottom of each catchment. These catchments are valuable in testing of the TOPMODEL software, as the previous data collected is ideally suited for parameterising and calibrating the model.

In addition the TOPMODEL has been applied to predict surface runoff from plots under the irrigated centre pivot at FAC. The total area under irrigation is 20.0 ha. The pivot is sub-divided into a series of rectangular farmlets (Figure 2), each with a strictly controlled stocking rate and well-defined nutrient loading imposed. The experimental design of field monitoring to measure water and nutrient runoff from the farmlets is described in detail by Fleming et al. (2003). Three irrigated catchments named Pivot A, Pivot B and Pivot C with respective areas of 1.3, 4.5 and 13.6 ha (Figure 2) have been defined naturally by topography and artificially by engineering works.

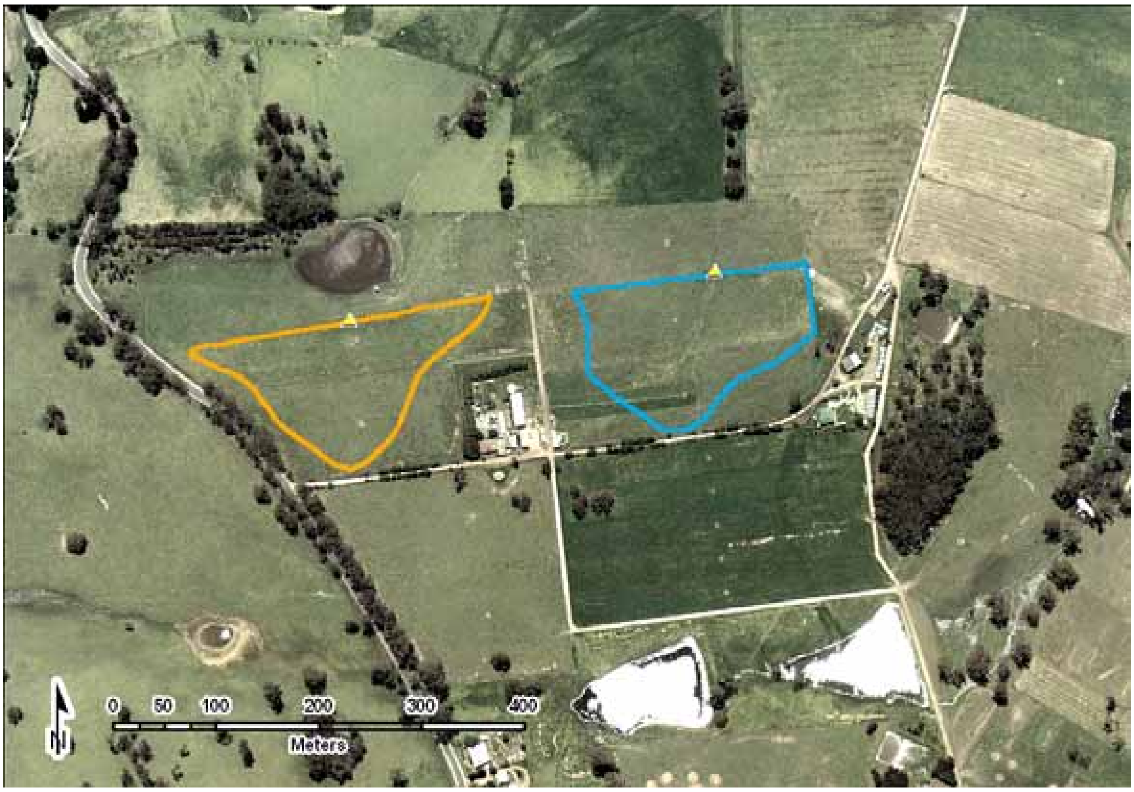


Figure 1. Flaxley West and Flaxley East dryland catchments. Yellow triangles represent location of instrumented flumes.

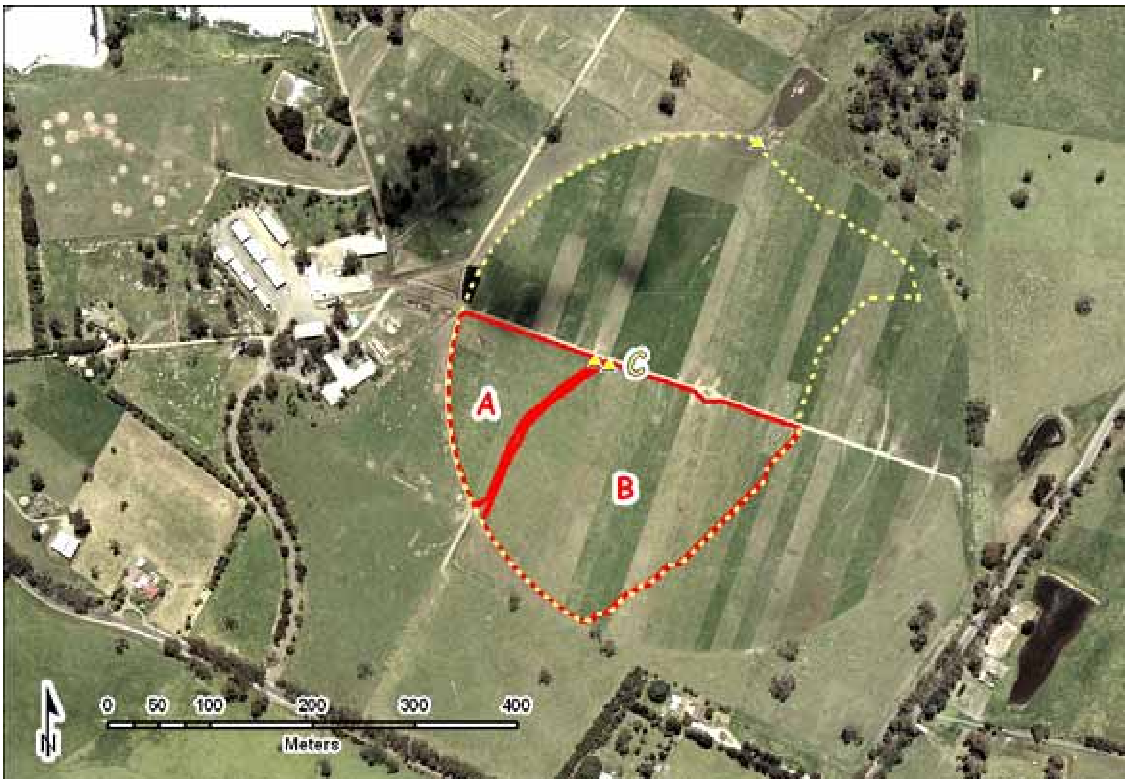


Figure 2. Pivot A, Pivot B and Pivot C irrigated catchments and relationship to individual farmlets. Yellow triangles represent location of monitoring stations.

## Runoff modelling

Prior to the modelling component of the study, the various input spatial data sets were required to be accurately located and georeferenced, to facilitate spatial and terrain analysis. This was achieved through the use of 0.5 m orthophotography for the FAC and accurate surveying of all relevant features in the study areas via differential GPS and ArcPad software (ESRI, 2002). These data sets were then linked back to the previously populated GIS data base for purposes of analysis and statistical output.

### *Derivation of topographic index distribution*

The essential data set requirement for TOPMODEL is a hydrologically correct, grided DEM. This data set is the basis for calculating the topographic index, the spatial distribution of which, defines the variable source areas for a catchment. For each of the two sets of catchments an appropriate resolution DEM was created from point data, using the ANUDEM interpolation package (Hutchinson, 1989). Previous studies have shown that the grid size for input DEMs used in hydrological modelling, should be smaller than the hillslope length, to adequately simulate the processes controlled by landform in defining the VSAs and to be better suited for detailed rainfall-runoff analysis (Zhang and Montgomery, 1994).

Once generated, the next step was to export the DEM data for each of the catchments into TOPMODEL, for computation of the ln(As/tanB) distribution (also referred to as ATB). The approach used here has been to integrate TOPMODEL within a GIS framework in a loose coupled manner (Huang and Jiang, 2002). That is, by import/export of data files between the GIS and TOPMODEL environments. This approach was aided by use of the Terrain Hydrological Analysis Library software (CRCCH, 2004). This toolkit package enabled the georeferenced derivation of multiple-flow direction ATB distributions and was critical to the development of the phosphorus load index.

A 2 m resolution, hydrologically correct DEM was created for Flaxley West and Flaxley East catchments from 2169 and 2964 points respectively. These were acquired from a real-time kinematic GPS (RTK) survey of the catchments in 2004. From these DEMs the statistical and spatial ATB distribution were derived. The spatial distribution of ATB for the two catchments can be seen in Figure 3. A comparison between catchments of the statistical distributions of ATB are shown in Figure 4.

Figure 3. Spatial distribution of ATB for dryland catchments. Low (light green) – high (dark green).

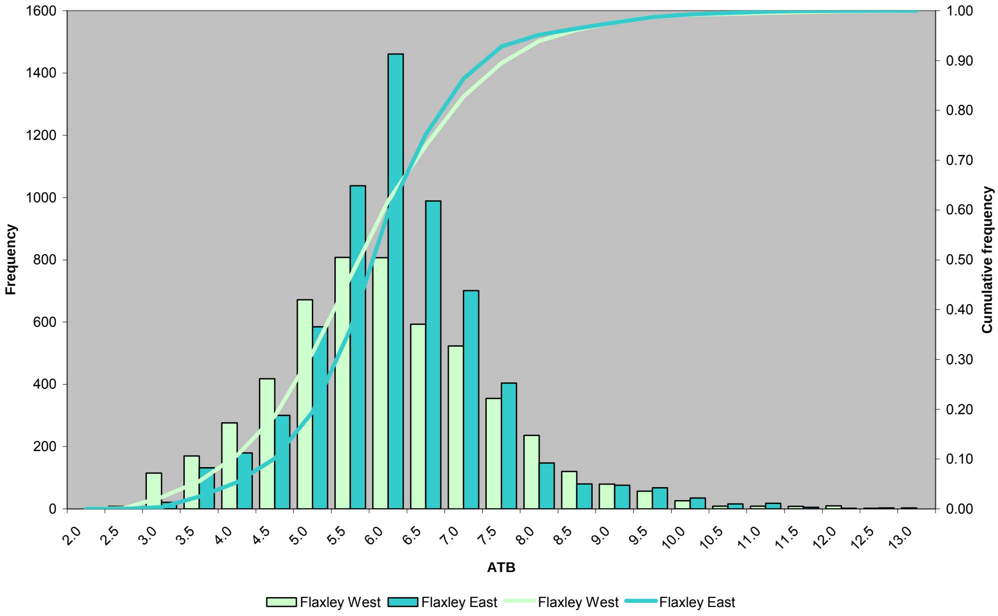


Figure 4. Distribution function of ATB for dryland catchments.

A detailed GPS survey of the pivot catchments was carried out in 2002, yielding 1740 accurate point, height measurements. From these points, a 2.5 m resolution DEM was created for the entire pivot. From this DEM, catchments A, B and C were delineated using flow direction and flow accumulation algorithms in ArcGIS (ESRI, 2003). The resulting catchment boundaries were then used to define the discrete DEMs which were the basis for deriving the ATB distribution. Figure 5 shows the spatial ATB distribution comparison for Pivot A, B and C catchments. A comparison between catchments of the statistical distributions of ATB are shown in Figure 6.

Figure 5. Spatial distribution of ATB for irrigated catchments. Low (light green) – high (dark green).

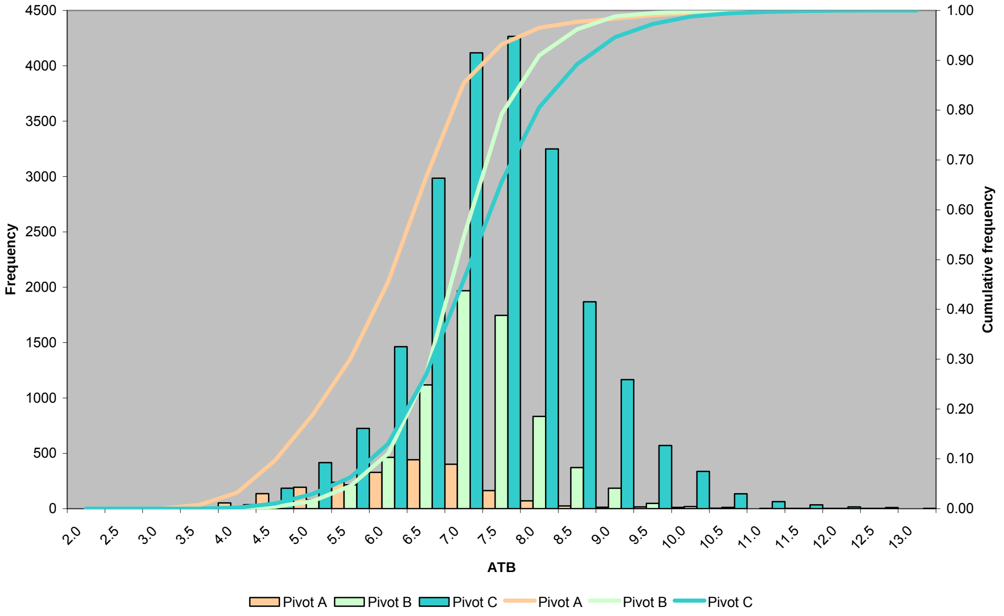


Figure 6. Distribution function of ATB for irrigated catchments.

### ***Parameterising and running TOPMODEL***

TOPMODEL is designed for the simulation of rainfall-runoff response times (as hydrographs) and prediction (both spatial and temporal) of saturated zones in the catchment. Being spatially distributed, TOPMODEL tries to model the dominant, spatially-variant processes of hydrology rather than the processes that are extremely difficult to prove or parameterise. As such there are a number of underlying basic assumptions that must be taken into account when interpreting any results from the model (Holko and Lepisto, 1997). These include:

- The dynamics of the saturated zone can be approximated by successive steady-state representations compatible with arealy averaged rates of recharge,
- The hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope (tanB); groundwater table and saturated flow are parallel to the local surface slope,
- The distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the water table,
- Grid cells with the same topographic index are hydraulically similar.

Using the above assumptions, TOPMODEL has been simplified to reduce the number of parameters that need to be calibrated to five (Table 1). Figure 7 shows the interactions between these five hydrological parameters. Beven and Kirkby (1979) describe the significance of the parameters and Quinn et al. (1995) discuss the effects of varying them.

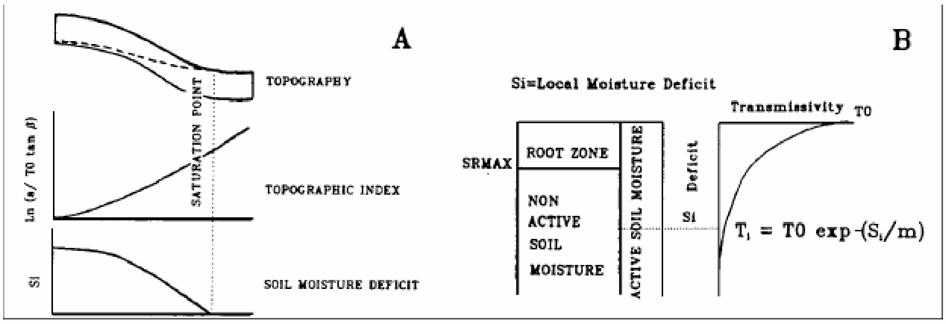


Figure 7. Interaction between TOPMODEL parameters, from Quinn et al. (1991).

Table 1. Hydrological parameters required for TOPMODEL.

| Parameter | Designation |
|---|---|
| m | Scaling parameter for the exponential transmissivity function or recession curve. Effectively the rate of rise or fall in the water table. (units of depth, m). |
| ln(To) | Natural logarithm of the effective transmissivity of the soil when just saturated. A homogeneous soil through out the catchment is assumed (units of $m^2$/hr). |
| SRmax | Maximum soil profile storage available for transpiration, i.e. an available water capacity (units of depth, m). |
| SRinit | Initial mean storage deficit in the root zone (an initialisation parameter, units of depth, m). |
| ChVel | An effective surface routing velocity for scaling the distance/area or network width function. Linear routing is assumed (units of m/hr). |

No attempt has been made to change the model structure for this study. Parameter values were optimised to improve the calibration, as opposed to being assigned by measurement or estimation. This was considered appropriate given that the catchments being modelled were gauged. The parameterisation for each of the catchments is listed in Table 2.

Table 2. Hydrological parameters used for each catchment.

| Parameter | Flaxley West | Flaxley East | Pivot A | Pivot B | Pivot C |
|---|---|---|---|---|---|
| m | 0.007 | 0.005 | 0.011 | 0.002 | 0.001 |
| ln(To) | 0.10 | 0.10 | 0.44 | 0.43 | 0.44 |
| SRmax | 0.07 | 0.07 | 0.07 | 0.06 | 0.07 |
| SRinit | 0.01 | 0.01 | -0.02 | -0.01 | -0.01 |
| ChVel | 39 | 42 | 42 | 35 | 45 |

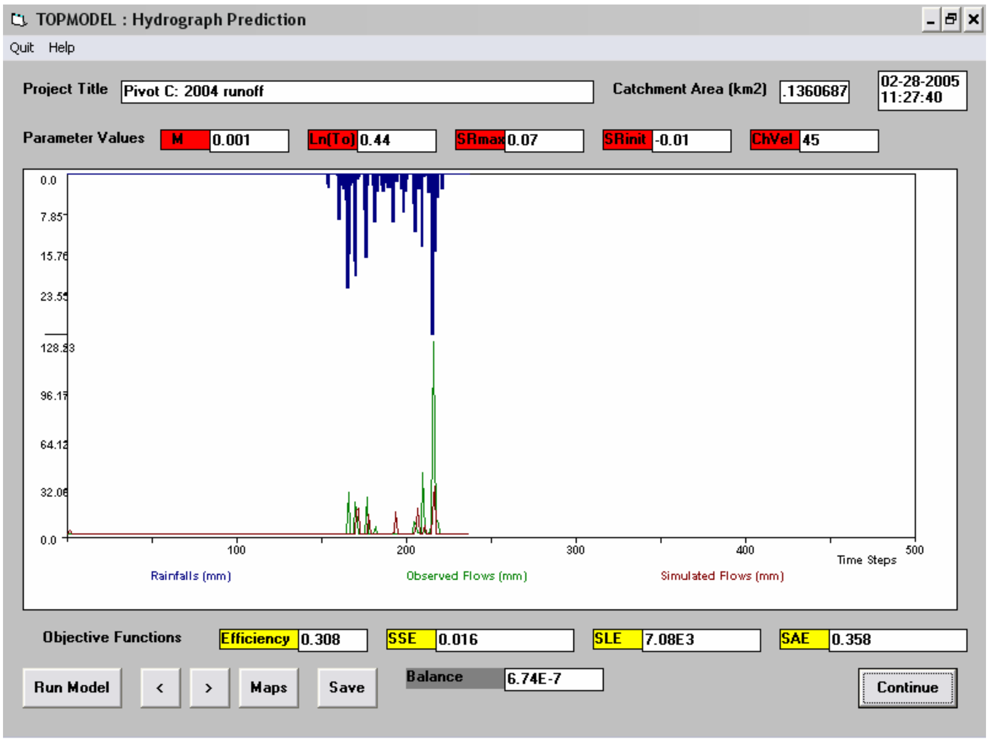
In terms of running TOPMODEL, the inputs required by the program are:

- ATB distribution function for the catchment (derived from a histogram analysis of the ATB data),
- ATB spatial distribution map for the catchment,
- Rainfall, potential evapotranspiration and observed flow data.

For the hydrological inputs to the TOPMODEL software, rainfall and discharge data were sourced from on-site readings, while evapotranspiration data was sourced from the Bureau of Meteorology's station at Echunga. The most appropriate timestep to run the model was explored. Comparison between model performance for hourly and daily timesteps indicated that there was no advantage to be gained in terms of sensitivity to events with an hourly timestep. It was decided instead, to run the model on a daily timestep. Model performance was assessed by linear regression and Nash-Sutcliffe Efficiency analysis (Nash and Sutcliffe, 1970).

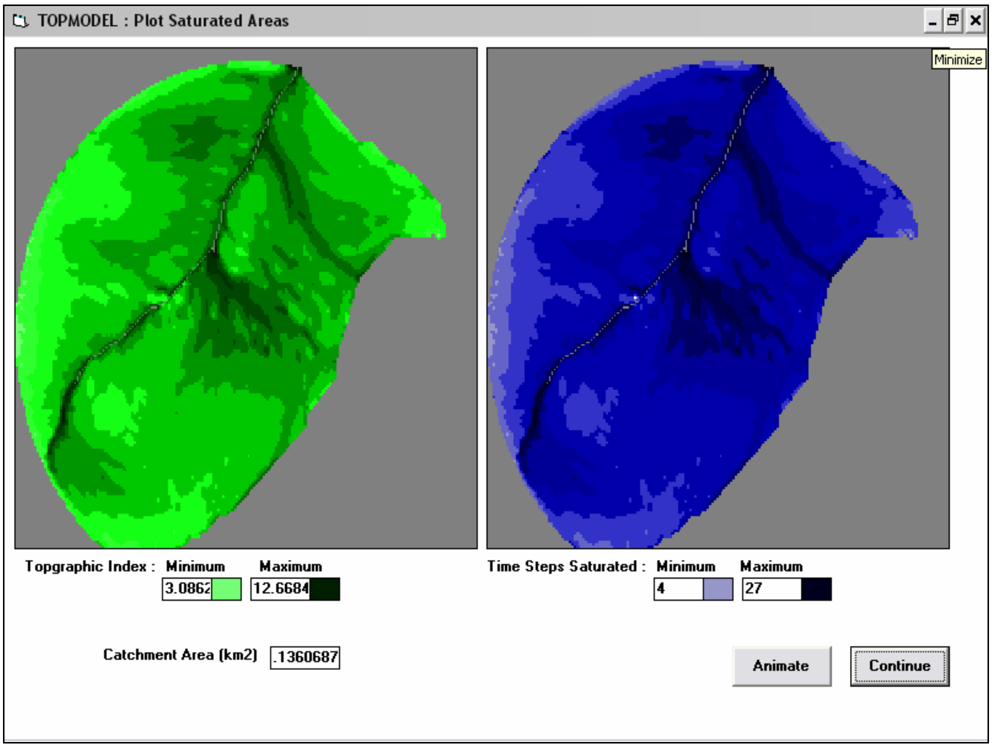
## Results and discussion

Results of TOPMODEL for the 2004 season, although inconclusive, are encouraging. Model performance does not appear to be influenced by the nature of the catchments (dryland or irrigated), as indicated by linear regression analysis. Examples of results for the Pivot C catchment are shown by hydrograph (Figure 8) and map of duration of saturation (Figure 9). The hydrograph shows observed and simulated runoff (x10 mm/day); rainfall (mm/day). The map shows ATB distribution (green); VSAs and duration of saturation (blue).



Project Title: Pivot C: 2004 runoff
Catchment Area (km2): .1360687
02-28-2005 11:27:40
Parameter Values: M 0.001; Ln(To) 0.44; SRmax 0.07; SRinit -0.01; ChVel 45
Objective Functions: Efficiency 0.308; SSE 0.016; SLE 7.08E3; SAE 0.358
Balance: 6.74E-7

Figure 8. Hydrograph for Pivot C, 2004 data.



Topgraphic Index : Minimum 3.0862 Maximum 12.6684
Time Steps Saturated : Minimum 4 Maximum 27
Catchment Area (km2) .1360687

Figure 9. Distribution (green) and duration (blue) of saturated areas for Pivot C, 2004.

Although hydrograph predictions are reasonable, TOPMODEL underestimates total runoff volumes for both dryland and irrigated catchments (Table 3). The exception was Flaxley West, where TOPMODEL accurately predicted runoff and Pivot A, where there was an over estimation of runoff volume. The result for Pivot A may be due to the very low runoff observed from this catchment in 2004, despite rainfall for the season sitting well within the historical data set.

Table 3. Comparison of measured and predicted runoff totals for 2004.

| Runoff | Flaxley West | Flaxley East | Pivot A | Pivot B | Pivot C |
|---|---|---|---|---|---|
| Measured (mm) | 9.3 | 22.5 | 4.1 | 32.8 | 36.5 |
| Predicted (mm) | 9.3 | 12.1 | 7.6 | 15.7 | 20.8 |
| Difference | 0.0 | 10.4 | 3.5 | 17.1 | 15.7 |
| $R^2$ | 0.68 | 0.45 | 0.36 | 0.66 | 0.41 |

## Phosphorus load modelling

This component of the study explored the feasibility of modifying the TOPMODEL inputs to allow modelling of P loads in surface waters coming off the dryland and irrigated catchments at FAC. The approach taken was that of developing a terrain-based, phosphorus load index (PLI) to simulate the spatial distribution of source areas of P, as related to soil P and position in the landscape. The PLI essentially replaces the function of the topographic index in TOPMODEL. This information along with rainfall, potential evapotranspiration and measured P load data for 2004 was input to the TOPMODEL framework, to produce predictions of P loads instead of runoff volumes. To differentiate between the two modelling frameworks, the modified model has been called TOPMODEL-PLI.

### *Interpolation of soil P surfaces*

The first stage in developing a PLI was to interpolate soil P surfaces for each of the five catchments using locally weighted splining of point data collected from soil sampling in early 2005. Soil phosphorus concentrations were derived as Olsen P in the 0 – 10 cm depth (Olsen $P_{0-10}$). For the purpose of later development of a runoff P surface for each of the catchments, Olsen $P_{0-10}$ surfaces were adjusted to an equivalent Olsen P in the 0 – 1 cm depth (Olsen $P_{0-1}$) using the following relationship (Dougherty 2005, pers. comm.; $R^2 = 0.94$):

$$\text{Olsen } P_{0-1} = 8.44 + (1.3465 \times \text{Olsen } P_{0-10}) \qquad \text{(Equation 1)}$$

For Flaxley West and Flaxley East catchments a 5 m resolution grided soil P surface was created from 43 and 74 sample points respectively. Figure 10 shows the Olsen $P_{0-1}$ (mg/kg) surfaces. A soil survey of 173 sample points was conducted over the pivot. From these data, a 5 m resolution grided soil P surface was created and clipped to each of catchments Pivot A, Pivot B and Pivot C. Figure 11 shows the Olsen $P_{0-1}$ (mg/kg) surfaces.

Figure 10. Olsen $P_{0\text{-}1}$ surfaces for dryland catchments, 2005.

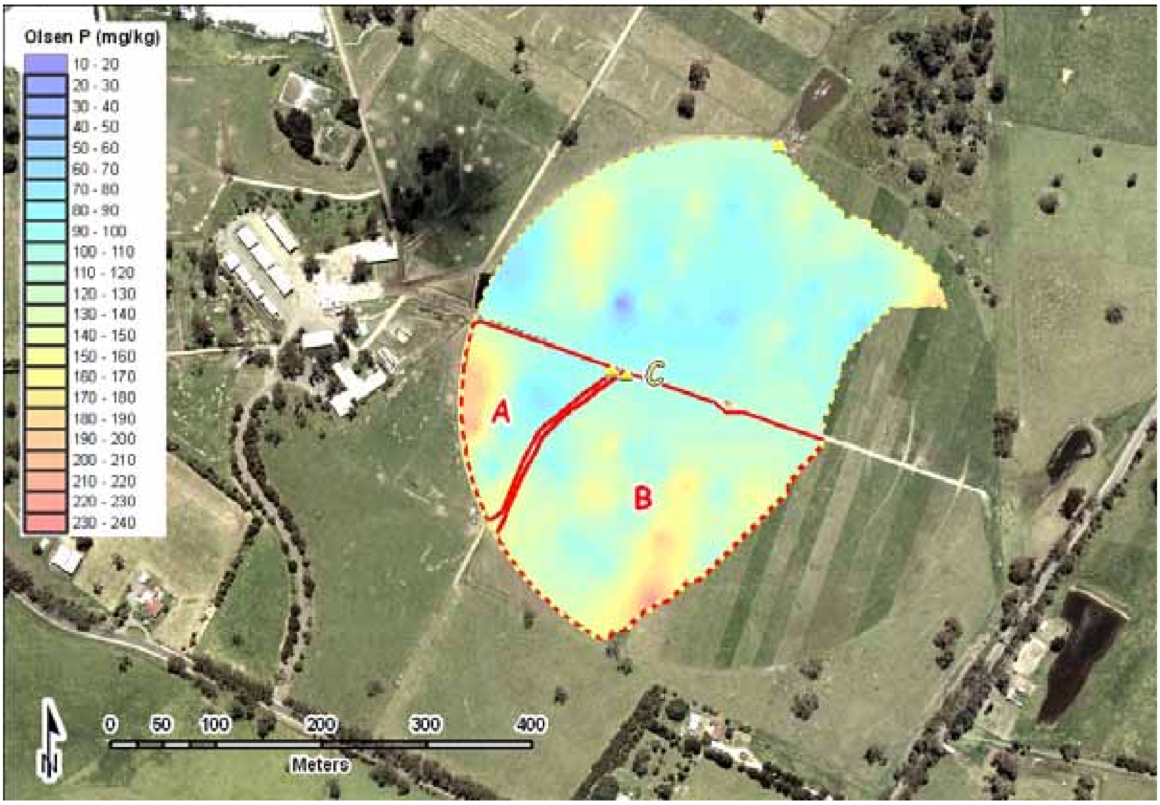


Figure 11. Olsen $P_{0\text{-}1}$ surfaces for irrigated catchments, 2005.

### *Soil P – runoff P relationships*

Subsequently, the soil P surfaces derived from sampling were used as inputs to the generation of runoff P surfaces for each of the catchments. Linear and curvilinear relationships have been empirically developed from rainfall simulations studies on both dryland and irrigated catchments. Total dissolved P (TDP) is used as the runoff P measure based on previous research which shows it to be the dominant form of P in runoff (Nash and Murdoch, 1997; Fleming and Cox, 1998). Rainfall simulations studies across Flaxley East catchment show a curvilinear relationship between Olsen $P_{0\text{-}1}$ (mg/kg) and runoff TDP (mg/L), defined by the following equation (Dougherty 2005, pers. comm.; $R^2 = 0.88$). This relationship has been applied to both Flaxley West and Flaxley East catchments, with the resulting surfaces for TDP (mg/L) shown in Figure 12.

$$\mathrm{TDP} = 0.0409e^{(0.0353 \times \text{Olsen } P_{0\text{-}1})} \qquad \text{(Equation 2)}$$

Similar rainfall simulations studies across the irrigated catchments show a linear relationship between Olsen $P_{0\text{-}1}$ (mg/kg) and runoff TDP (mg/L), defined by the following equation (Fleming 2005, pers. comm.; $R^2 = 0.63$). This relationship has been applied to Pivot A, Pivot B and Pivot C catchments, with the resulting surfaces for TDP (mg/L) shown in Figure 13

$$\mathrm{TDP} = -0.1084 + (0.016622 \times \text{Olsen } P_{0\text{-}1}) \qquad \text{(Equation 3)}$$

Figure 12. Areas contributing to runoff P (as TDP) for dryland catchments, 2005.

Figure 13. Areas contributing to runoff P (as TDP) for irrigated catchments, 2005.

### Development of phosphorus load index (PLI)

The aim in developing a terrain-based, phosphorus load index (PLI) was to simulate the spatial distribution of source areas of P which are relatable to variable source runoff. To achieve this, runoff P (TDP) surfaces were combined with the previously defined spatial distribution of ATB, using Terrain Hydrological Analysis Library software (CRCCH, 2004). Various combinations of TDP and ATB were explored, with the purpose of generating an index which is representative of the processes occurring in the catchment, while also being acceptable input to the TOPMODEL framework. The weighting of inputs that were decided upon is:

$$PLI = ATB + 2 \times TDP \qquad \text{(Equation 4)}$$

This index has been calculated for each of the dryland and irrigated catchments, prior to input to TOPMODEL and scaled such that the higher the PLI, the more likely a cell is to contribute a higher amount of P. The spatial distribution of PLI for Flaxley West and Flaxley East catchments can be seen in Figure 14. A comparison between catchments of the statistical distributions of PLI is shown in Figure 15. Figure 16 shows the spatial PLI distribution comparison for Pivot A, Pivot B and Pivot C catchments. A comparison between catchments of the statistical distributions of PLI is shown in Figure 17.

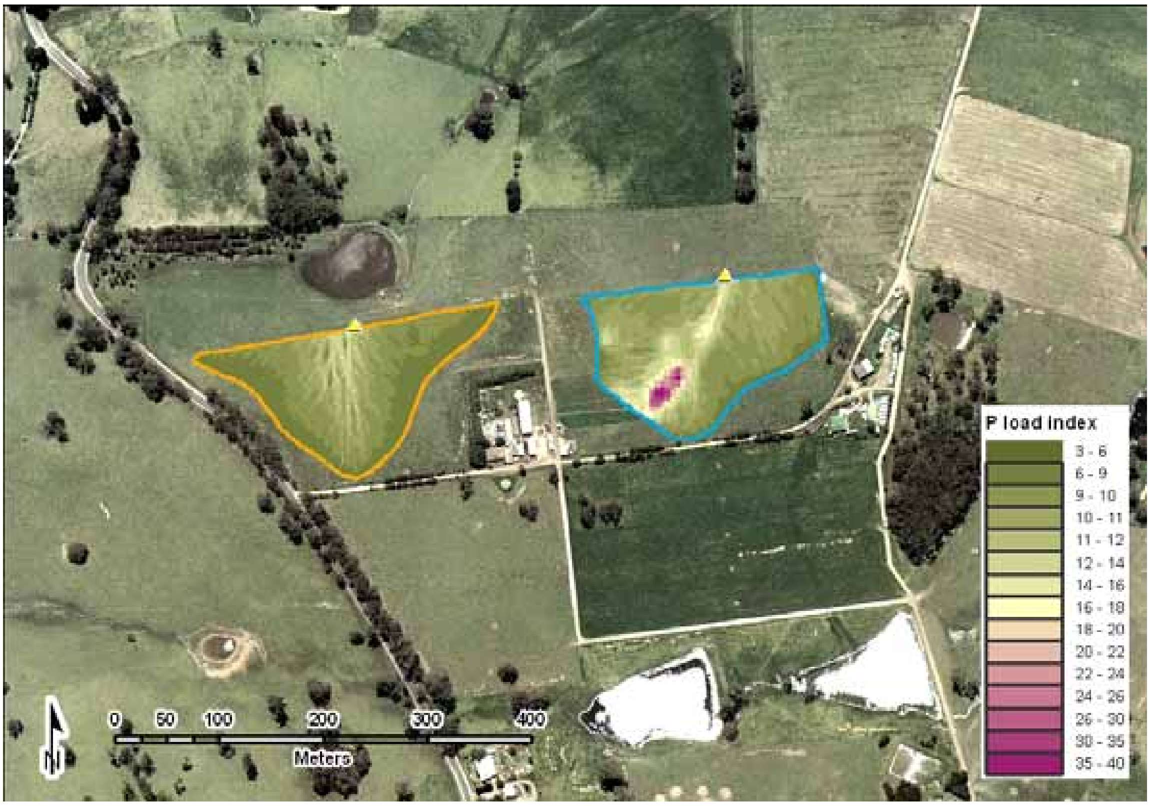


Figure 14. Spatial distribution of PLI for dryland catchments.

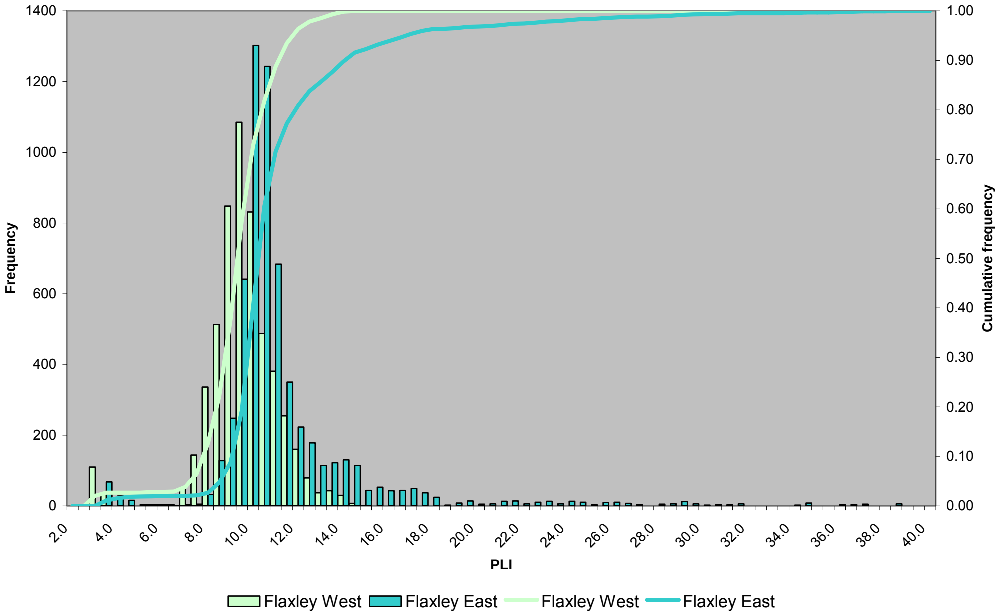


Figure 15. Distribution function of PLI for dryland catchments.

Figure 16. Spatial distribution of PLI for irrigated catchments.

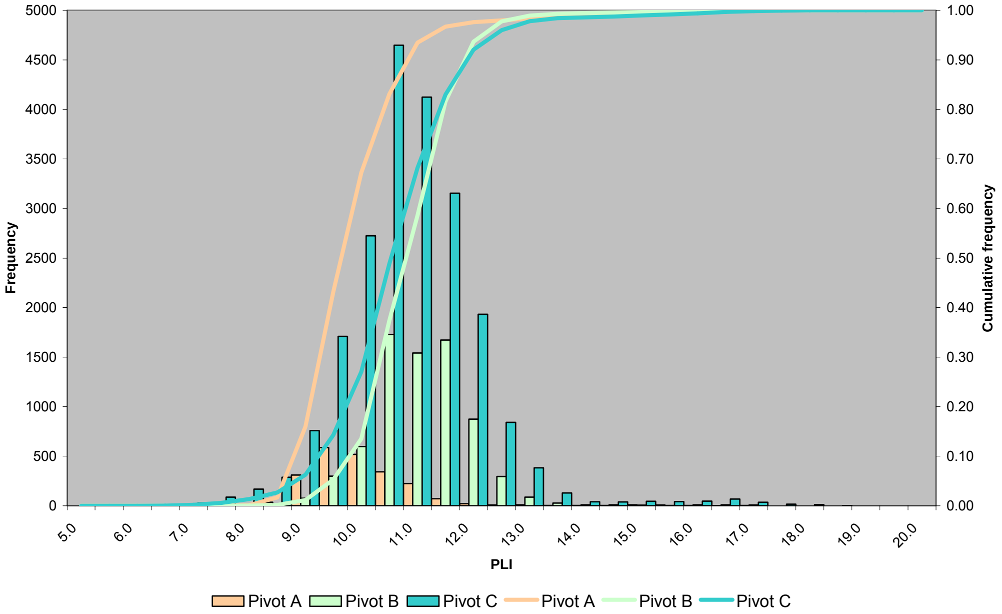


Figure 17. Distribution function of PLI for irrigated catchments.

### ***Parameterising and running TOPMODEL-PLI***

For predicting phosphorus loads coming off the catchments, the inputs to TOPMODEL have been modified to become:

- PLI distribution function for the catchment (derived from a histogram analysis of the PLI data),
- PLI spatial distribution map for the catchment (as relatable to variable source areas),

- Rainfall, potential evapotranspiration and observed phosphorus load data.

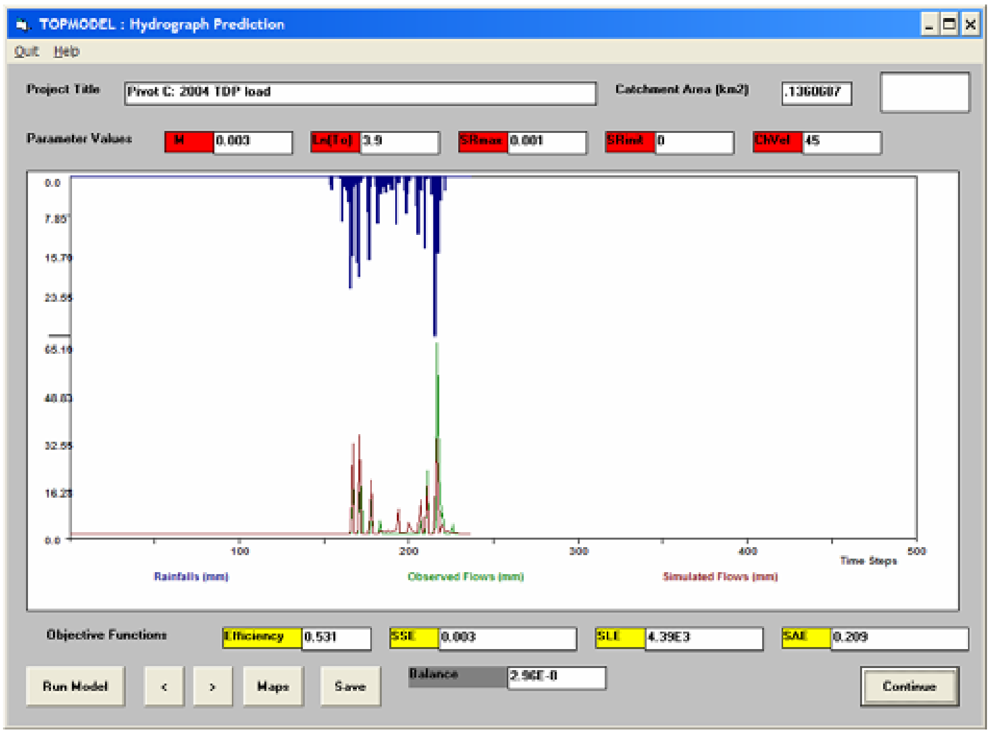
As was the case with runoff modelling, it was decided to run TOPMODEL-PLI on a daily timestep. All parameter values have been optimised to improve the calibration based on phosphorus load data measured off each of the catchments during 2004. The exception was the surface routing parameter (ChVel), which was held the same as for runoff modelling. The parameterisation for each of the catchments is listed in (Table 4).

Table 4. PLI input parameters used for each catchment.

| Parameter | Flaxley West | Flaxley East | Pivot A | Pivot B | Pivot C |
|---|---|---|---|---|---|
| m | 0.019 | 0.013 | 0.018 | 0.003 | 0.003 |
| ln(To) | 1.2 | 1.3 | 3.3 | 3.5 | 3.9 |
| SRmax | 0.01 | 0.01 | 0.001 | 0.001 | 0.001 |
| SRinit | 0 | 0 | 0 | 0 | 0 |
| ChVel | 39 | 42 | 42 | 35 | 45 |

### *Results and discussion*

An example of results for the Pivot C catchment are shown by the hydrograph (Figure 18) of observed and simulated P load ($x10^{-1}$g/ha); rainfall (mm/day) and map (Figure 19) showing PLI distribution (green); Total P contribution (blue).



Project Title: Pivot C: 2004 TDP load

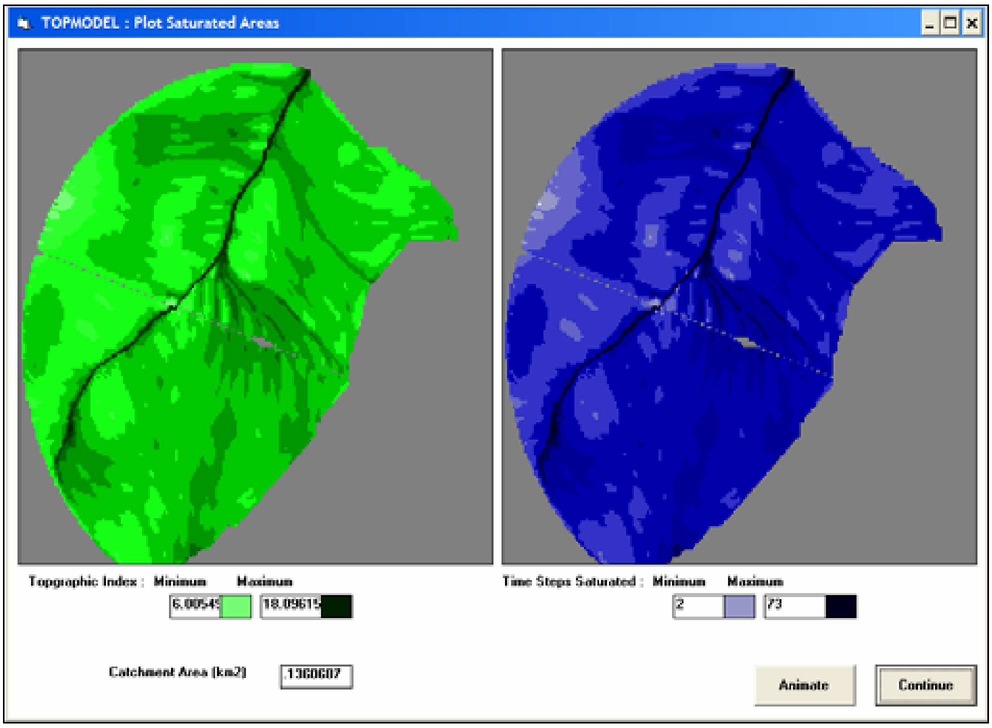
Catchment Area (km2): .1360607

Parameter Values: M 0.003; Ln(To) 3.9; SRmax 0.001; SRinit 0; ChVel 45

Objective Functions: Efficiency 0.531; SSE 0.003; SLE 4.39E3; SAE 0.209

Balance: 2.96E-0

Figure 18. P load prediction for Pivot C, 2004 data.



Topographic Index : Minimum 6.00549 Maximum 18.09615

Time Steps Saturated : Minimum 2 Maximum 73

Catchment Area (km2) .1360607

Figure 19. Distribution (green) and total contribution (blue) of P load sources for Pivot C, 2004.

TOPMODEL overestimates total P loads off all catchments (Table 5). The predictions could not be improved by adjusting the parameters. Improved predictions of P load were obtained by adjusting the ChVel parameter, but this was not considered appropriate, given that the catchment morphologies were unchanged. However the decision to hold this parameter the same as for runoff modelling, seriously compromised model performance for both dryland catchments and Pivot A catchment.

Table 5. Comparison of measured and predicted P load totals for 2004.

| P load | Flaxley West | Flaxley East | Pivot A | Pivot B | Pivot C |
|---|---|---|---|---|---|
| Measured (g/ha) | 52 | 394 | 135 | 1740 | 2000 |
| Predicted (g/ha) | 346 | 922 | 891 | 2301 | 2299 |
| Difference | 294 | 528 | 756 | 561 | 299 |
| $R^2$ | 0.22 | 0.22 | 0.38 | 0.74 | 0.54 |

### ***Uncertainty estimates***

The generalised likelihood uncertainty estimation (GLUE) methodology proposed by Beven and Binley (1992) was used to assess the P load predictions and to set confidence limits for Flaxley East and Pivot C catchments as examples of estimation of uncertainty in TOPMODEL-PLI. GLUE has been developed from an acceptance of the possible equifinality of models, that is, different sets of model parameters may be equally likely as simulators of the real system (Beven and Freer, 2001). It works with multiple sets of parameters, typically via Monte Carlo sampling, and applies likelihood measures to estimate the predictive uncertainty of the model. Model realisations are weighted and ranked on a likelihood scale via conditioning on observations and the weights are used to formulate a cumulative distribution of predictions. Model parameter sets with almost zero likelihood can be classified as non-behavioral and rejected.

The GLUE framework was used to analyse 1000 random parameter sets derived from Monte Carlo simulation. Predictive performance for each of the parameter sets was evaluated using the Nash-Sutcliffe efficiency measure (E). Plots of E versus predicted cumulative P load for each parameter set were made to assess the sensitivity of parameters to simulation of P loads. Based on the cumulative distribution of predictions and using E as the likelihood measure, uncertainty bounds were calculated for the predictions. The results for best overall model efficiency (as determined by GLUE) compared to measured observations and the 95th percentile are shown for Flaxley East (Figure 20) and Pivot C (Figure 21).

For both catchments, the dynamics of the events and the P loads produced have been reasonably well captured, within the uncertainty limits of TOPMODEL-PLI. The improved predictive nature of the very high P load observation of the 4th August 2004, for Pivot C suggests further optimisation of the original model parameters would capture the event. It is worth noting that small load events predicted by TOPMODEL-PLI but not observed, may in fact be real. This may be due to field instrumentation not being sensitive enough to detect such small events. The predicted P load totals of 628 g/ha (Flaxley East) and 1827 g/ha (Pivot C) from GLUE simulation compare more favourably to the measured P load totals off each catchment as originally modelled.

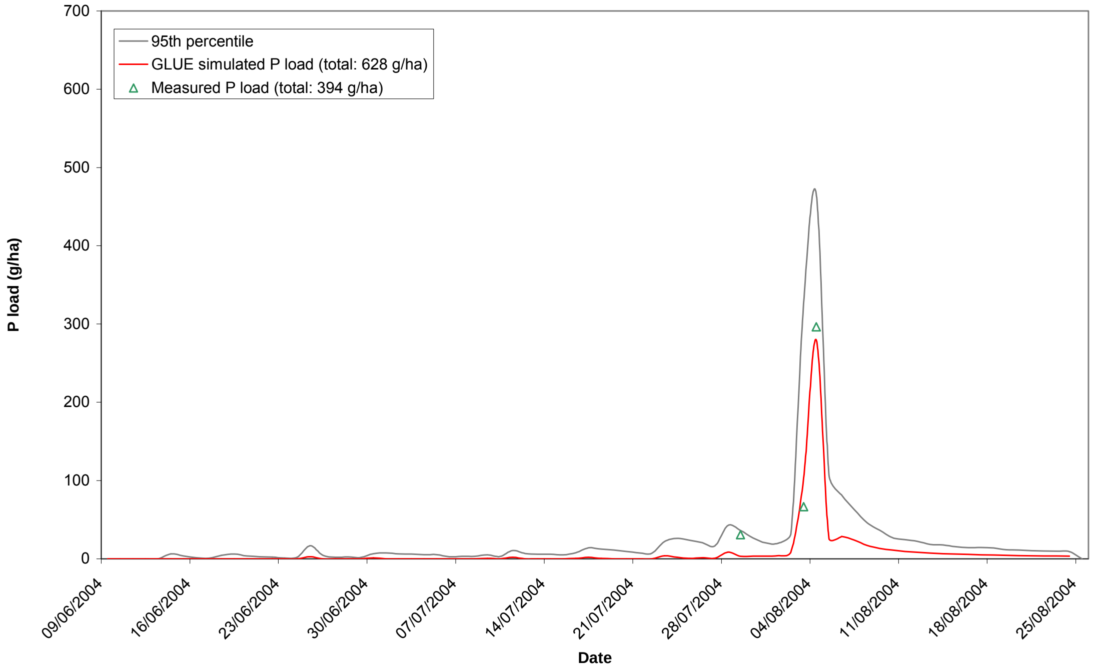


Figure 20. Measured P loads compared with the GLUE simulation of the best overall model efficiency and 95th percentile uncertainty estimation for Flaxley East, 2004.

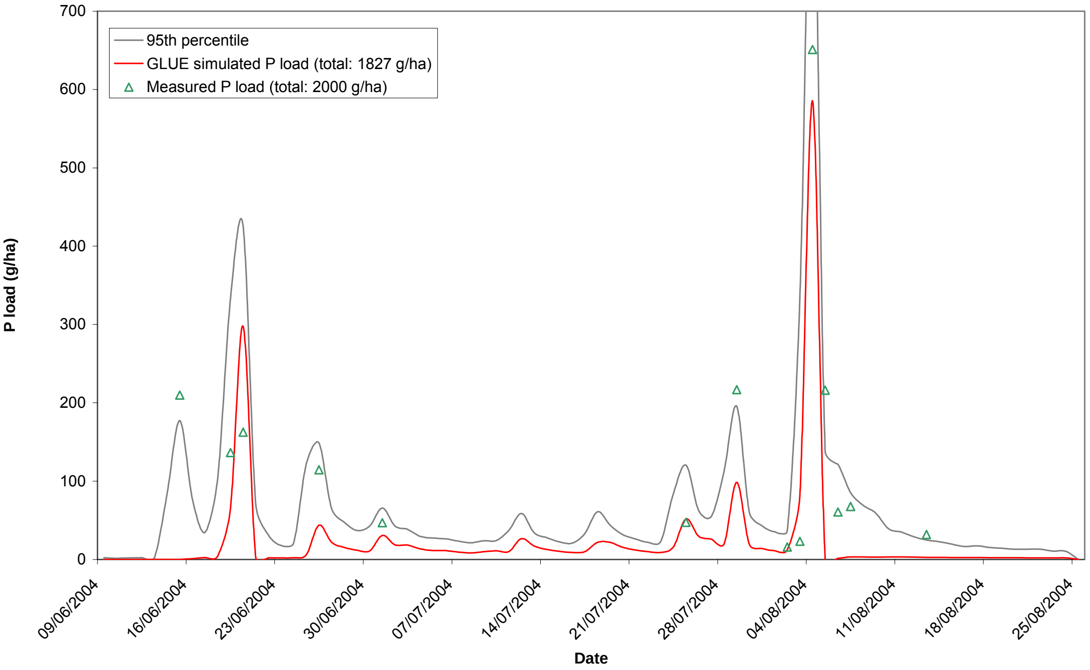


Figure 21. Measured P loads compared with the GLUE simulation of the best overall model efficiency and 95th percentile uncertainty estimation for Pivot C, 2004.

## Conclusions

TOPMODEL was found to model runoff for dryland and irrigated catchments with some success, based upon one season of monitoring data. The timing of runoff events was reasonably accurately predicted. However, there was a tendency to over predict runoff volumes from those catchments with a high average ATB (Flaxley East, Pivot B and Pivot C) and under predict runoff volumes from catchments with a low average ATB (Flaxley West and Pivot A). Variable source areas have been defined for both dryland and irrigated catchments within the TOPMODEL framework. Based on anecdotal evidence from field observations, these VSAs reflect well, areas that contribute to water runoff in these catchments.

Results of modelling P loads using the phosphorus load index, incorporated into TOPMODEL for dryland and irrigated catchments were encouraging but TOPMODEL-PLI tending to over estimate total P loads volumes off all catchments. This is particularly the case for Flaxley West and Pivot A catchments. However a case assessment of the predicted P loads for Flaxley East and Pivot C catchments, showed they were well within acceptable error (95th percentile). The modelled P load results may, in part be due to the accuracy of the phosphorus load index that was used in TOPMODEL. Two issues - the interpolation of soil P surfaces (related to sampling strategy) and robustness of the soil P-runoff P relationship (which was found to vary by soil type and management practice) may have impaired the PLI. Although the prediction of P load was within acceptable error it may be improved by further research into the soil P:runoff P relationship, allowing this method to be used in other catchment environments across a range of soils and scales.

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