# To Split or Lump? Influence of Spatial Representation in Flow and Water Quality Response Simulation

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## EXTENDED ABSTRACT

Hydrology models are widely used to simulate the generation and transport of nutrients from catchments to streams. While spatially distributed models exist, many catchment scale models use a semi-lumped approach with aggregated response units based on land use. However, lumped models do not explicitly consider the interaction of runoff from different areas and often route runoff directly to the catchment outlet, without considering how these interactions may affect solute export. This paper addresses the question "what differences are introduced due to this spatial lumping?" by comparing the results of distributed and lumped models of a catchment. The spatially explicit hydrological model THALES was used to simulate a variety of theoretical catchments, each with two different landscape units (**Figure 1**). The landscape unit pairs were arranged so that one unit occupied the upper slopes while the other unit occupied the lower slopes. Soil landscape units varied in terms of either land use, soil hydrologic parameters or soil nutrient concentration. The simulation results were analysed to explore the influence of explicitly considering spatial arrangement on the catchment hydrological response and solute export. The modelling results show how the response of the surface and subsurface flows might vary for different spatial arrangements due to spatial interaction of the runoff and infiltration processes between different land units (**Figure 2**). The magnitude and importance of the differences varies according to the land use and runoff processes of the catchment. The different hydrologic response influences the timing and load of solutes exported from the catchment. The results from the spatially explicit model are compared with a lumped model, calibrated against the individual land uses. The results show that the lumped model cannot account for the variation in spatial location, especially if the dominant runoff process is located upstream of the catchment outlet. Even if the dominant runoff mechanism for the two soil types is the same, spatial position and connectivity are important if the soils have different nutrient concentrations. In this case, localized generation of runoff near the catchment outlet would account for most of the nutrient exported. In lumped models, runoff is generated independently for each land unit and interaction effects are not taken into account. Thus, lumped models either over or under predict the loads exported depending on the spatial location and dominant runoff processes.

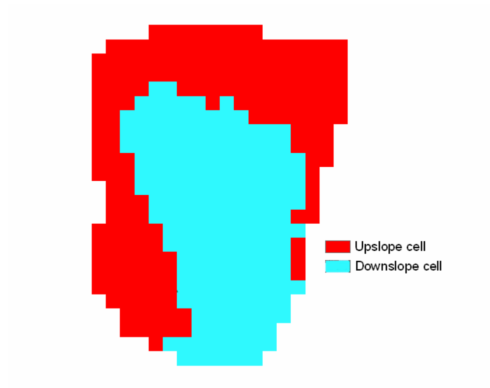


**Figure 1**: Upslope and downslope cell used to divide the catchment into soil types

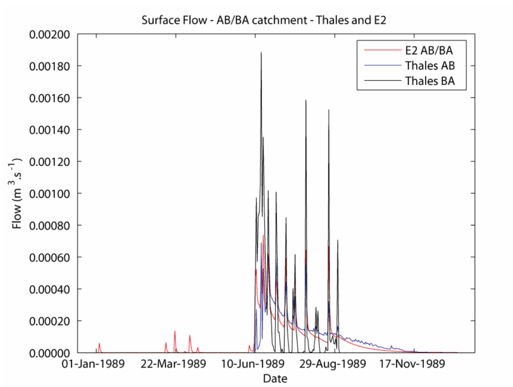


**Figure 2**: Hydrographs for the AB/BA catchment.

## 1. INTRODUCTION

Whilst it is clear that the export of nutrients is directly linked to the hydrology of a catchment, the role and importance of each different flowpath is not always straightforward. The response of a catchment to a rainfall event is directly linked to the connectivity of flow paths and the scale of the catchment (Hill 1993; Cirmo and McDonnell 1997; Cammeraat 2002; Stieglitz *et al.* 2003; Haygarth *et al.* 2005). Other characteristics such as rainfall intensity and duration or antecedent soil moisture conditions may also change catchment behaviour. Grayson *et al*. (1997) propose two dominant catchment types: i) dry - with hydrological region disconnected without spatial organization in soil moisture patterns, and ii) wet, with hillslopes connected and organized spatial patterns of soil moisture. While Grayson et al. (1997) worked in a landscape dominated by saturation excess overland flow processes, similar observations have been made in subsurface flow cases (Tromp-van Meerveld and McDonnell 2006). As the hydrologic connection also influences runoff volume it has a significant impact the load of any constituents as well as the concentration.

Nutrient response of a catchment therefore depends not only on the total runoff response but also on the different flowpaths and their interaction. These interactions can contribute to the differences in shapes between a pollutograph and a hydrograph for a rainfall event.

The influence of catchment condition and flowpaths on the export of nitrate and magnesium from a 46 $km^2$ grassland catchment in the UK is illustrated in a large study by Webb and Walling (1985). The study analysed more than 600 storms events and the associated hydrographs and pollutographs. For Mg, the pollutographs invariably reach a minimum concentration during the rising phase of the hydrograph, indicating dilution effects. While the general response for nitrate was for increasing concentration with discharge (ie, concentration effects), dilution was observed for some storms. In their study, Webb and Walling (1985) link these differences to soil moisture and the different processes generating runoff.

Consistent dilution behaviour occurs during winter when soil moisture deficits are low and saturated areas around channels and riparian zones have expanded. Then the baseflow originates from topsoil horizons and is nitrate-rich. Also, production of low nitrate quickflow that dilutes the baseflow is favoured during events. In contrast, from late spring to early autumn months, soil moisture is low and rapid response areas are diminished, so most rainfall enters the soil profile and is transported as nitrate rich throughflow, resulting in a concentration effect. Although these responses have a seasonal aspect, they can occur at different times of the year, depending on the prevailing antecedent hydrological conditions at the time of the event. The influence of pathways is not limited to nitrogen, but can also affect other nutrients such as phosphorus, leading to different responses such as dilution and concentration effects (Haygarth *et al.* 2004).

The models used to describe constituent export in the literature vary significantly in complexity, from models based on simple areal rates to complete descriptions of hydrology, plant growth and nutrient cycling. However, added complexity does not guarantee superior predictive capabilities (Merritt *et al.* 2003). Spatially distributed models usually require detailed input data, are more difficult to set up and have relatively high computational times when compared with lumped models.

Areal models often use a generation rate based on land use multiplied by the area of that specific land use, but they cannot differentiate between high and low runoff areas within the land use. To overcome this limitation, lumped models using conceptual hydrology descriptions to assess variations in loads due to land use and hydrological response have increased in popularity, especially in Australia. Examples include the EMSS (Vertessy *et al.* 2001) and the E2 catchment modelling software (Argent *et al.* 2005).

In the EMC/DWC model of E2, loads are calculated as the product of dry weather pollutant concentration (DWC) and baseflow volume, and event mean concentration (EMC) and flow for stormflow. Different land uses are assigned a different set of EMC and DWC values. There are usually a limited number of data sets to calibrate and validate these models, with EMCs and DWCs usually derived from small datasets for a limited set of conditions. These parameters are usually obtained from paddock or hillslope scale studies.

In systems like E2, catchment heterogeneity is addressed by dividing the catchment into response units. Each unit is considered to generate runoff and export constituents independently, without considering connectivity and flowpath variation. Instead, runoff from each unit is transferred directly to the outlet and summed with the runoff from the other areas, with or without time lags.

As such, lumped models cannot consider interaction effects between units. As a consequence, loads may be either over or underestimated and temporal variations may be poorly captured. To evaluate the magnitude of this error, this paper describes a comparison between a spatially explicit model, Thales (Grayson *et al.* 1995; Western and Grayson 2000) and a lumped model built using E2. The comparison uses soils with different properties and/or different concentrations to demonstrate that lumped models fail to capture behaviours caused by local generation of runoff.

## 2. MODEL DESCRIPTIONS

Two soil combinations were used to evaluate the implications of ignoring the connectivity of landscapes in lumped models such as those built with E2. One of the combinations used two soils, one dominated by saturation excess (Soil A) and the other by infiltration excess (Soil B). The other combination used soil dominated by saturation excess, but with slightly different properties and different concentrations.

For each pair of soils, two simulations were run using Thales, first with one soil located on the upper slopes and the other on the lower slopes and the second with the soils reversed. The results of these two simulations are then compared with only one E2 simulation, because the model built with E2 ignored spatial arrangement.

### 2.1. Thales

Thales is a distributed hydrological model designed for application to small catchments (generally <100km$^2$). The model used in this study was a modification of the Thales framework (Grayson *et al.* 1995; Western and Grayson 2000). Thales represents the landscape using a grid-based element network, and flow (both surface and subsurface) is routed from an element to its two steepest descent neighbours. Flow allocation uses the approach developed by Tarboton (1997) for hillslope elements and to the steepest descent neighbour in channels. The soil can be represented by as many layers as desired. Lateral movement of water is possible in all layers, as well as by surface flow.

The model incorporates the following processes:

- Subsurface lateral flow (kinematic wave)
- Overland flow (kinematic wave)
- Infiltration excess runoff generation
- Saturation excess surface runoff generation
- Exfiltration of soil water
- Runon infiltration of overland flow
- Deep seepage
- Evapotranspiration

Infiltration excess overland flow is simulated using an approximate solution for the infiltration rate based on constant head conditions and time compression as described in Kim (1996). The model assumes Brooks and Corey's relationship for soil water retention and hydraulic conductivity characteristics. Lateral subsurface flow occurs when a hydrostatic soil moisture profile within the layer indicates that saturated conditions will exist.

This version of Thales has been modified to include the nutrient transport of a purely soluble solute and another solute that is in equilibrium with an adsorbed phase. For the dissolved solute, each soil layer and the surface contain a solute store. Solute can enter the store with any water inputs to a cell, and can leave with any water outputs, with the exception of evapotranspiration. For the soil surface, solute can be added as a flux to either represent rainfall input and/or addition by some management action. The movement of solution is calculated by mass balance, assuming complete mixing within the soil element. For the adsorbed solute, an additional store exists for every soil layer but not for the surface which is assumed to have only a solute store. The net rate of adsorbtion or desorption is described as:

$$\Delta = k_{Ads} . C_{Ads\,Store}\left(1 - \frac{M_{Ads}}{M_{Max}}\right) . V_W - k_{Des}\left(\frac{M_{Ads}}{M_{Max}}\right) . V_S \, . \, \rho \quad (1)$$

where $k_{Ads}$ is the adsorption rate (s$^{-1}$), $C_{AdsStore}$ is the store concentration (kg.m$^{-3}$), $M_{Ads}$ is the adsorbed mass (kg) and $M_{Max}$ is the maximum adsorbed mass (kg), $V_W$ is the volume of (soil) water, $k_{Des}$ is the desorption rate coefficient (s$^{-1}$), $V_S$ is the soil volume (m$^3$) and $\rho$ is the soil bulk density (kg.m$^{-3}$).

The top soil layer is also divided into two sublayers to allow the representation of a higher concentration near the surface. For this thin layer, the solute can also be transported into the surface flow via diffusive transport using the following:

$$W_A = k' . A . \Delta C \quad (2)$$

where $W_A$ is the mass transfer rate, $A$ is the mass transfer area (cell area), $\Delta C$ is the difference between the thin layer solute concentration and the surface flow concentration and $k'$ is the mass transfer coefficient given by (Thibodeaux 1996):

$$k' = \frac{0.114v^*}{Sc^{2/3}} \quad (3)$$

where $v^*$ is the friction velocity and *Sc* is the Schimdt number, defined as the ratio between the kinematic viscosity and *D,* the solute diffusivity in water.

### 2.2. Catchment description

The study catchment uses the topography of the western portion of the Tarrawara catchment (Western and Grayson 2000), in southern Victoria. A temperate climate is assumed and there is a significant rainfall deficit in summer and excess in winter. The terrain consists of smoothly undulating hills. For the simulations, the annual rainfall was 588.4 mm and the annual potential evapotranspiration was 1045 mm. For all scenarios, the model time step was 6 minutes and the simulation period was one year

The DEM used in the model consisted of 353 10 x 10 m cells for a total of 3.53 ha (**Figure 3**). The catchment was also divided into upslope and downslope sections (**Figure 1**).

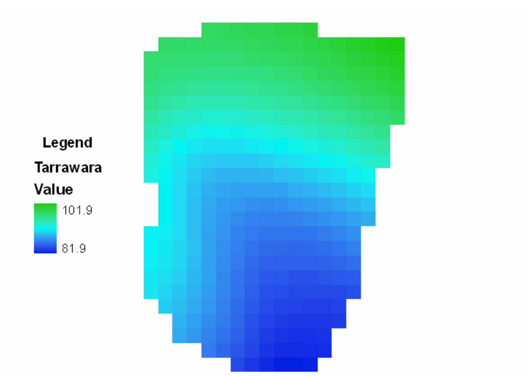


**Figure 3**: Digital Elevation Model used in the model

Three soil layers, each with different soil properties were used. The soil and surface property values adopted during the simulations are shown in **Table 1** and **Table 2**. The soil depth for layers 1 and 2 is 0.2 m, and for layer 3 is 0.225 m.

**Table 1**: Soil parameters for all layers

| Soil | Hydraulic Conductivity (mm/h) | Wilting Point | Porosity |
|---|---|---|---|
| A | 13.3 (V) / 3.0 (H) | 0.1 | 0.4 |
| B | 400 | 0.15 | 0.5 |
| C | 266.6 | 0.1 | 0.4 |

The initial soil moisture conditions were different for each soil layer but were kept constant throughout the study.

**Table 2**: Surface parameters

| Surface layer | Canopy capacity (m) | Fraction Cover | Mannings n |
|---|---|---|---|
| Soil A & C | 0.002 | 1 | 0.4 |
| Soil B | 0.01 | 0.5 | 0.3 |

### 2.3. Water quality parameters

In all simulations in this study, the initial concentrations of phosphorus and salt were kept constant (**Table 3**). For soil B, all concentrations are half of the ones used in soils A and C. The other properties adopted are:

- $k_{Ads}$ = 0.0001 $s^{-1}$ ;
- $M_{Max}$ = 0.01 kg;
- $k_{Des}$ = 0.000000002 $s^{-1}$ ;
- $\rho$ =2.65 $kg.m^{-3}$;

**Table 3**: Water quality concentration for different solutes and soil layers for soils A & C.

| Layer | Salt (kg/kg) | Adsorbed Phosphorus (kg/kg) | Solute Phosphorus (kg/kg) |
|---|---|---|---|
| Thin layer | N/A | 0.00004 | 0.000013 |
| 1 | 0.000035 | 0.00003 | 0.000008 |
| 2 | 0.000025 | 0.000003 | 0.000001 |
| 3 | 0.000025 | 0 | 0 |

### 2.4. E2 calibration and parameters

Daily flows, actual evapotranspiration and daily loads from the Thales simulation were used to calibrate the flows and water quality parameters in E2. The first step was to obtain the parameters to simulate the hydrology. The model adopted was AWBM (Boughton 2004). AWBM is a water balance model that uses 3 surface stores to simulate partial area runoff, with the water balance of each surface store calculated independently of the others. When runoff occurs from a store, part of the runoff becomes recharge of the base flow, based on the baseflow index. The remainder is allocated to surface flow. The AWBM models were calibrated to the Thales results for simulations where one soil type was used for the entire catchment using the Nash-Sutcliffe (Nash and Sutcliffe 1970) criteria as the primary objective function and the flow duration curve as the secondary. The calibration results are shown in **Table 4** .

**Table 4**: Runoff Coefficient, Baseflow Index and Nash Sutcliffe for the E2 comparison

| Case | Baseflow Index Thales | Runoff Coefficient Thales | Nash Sutcliffe Coeeficient | Runoff Coefficient E2 |
|---|---|---|---|---|
| A | 0.0004 | 0.054 | 0.86 | 0.046 |
| B | 0.0133 | 0.149 | 0.67 | 0.133 |
| C | 0.01 | 0.174 | 0.72 | 0.144 |

For each of the soils, the EMC and DWC were determined using the E2 calibration tool until the total annual load and visual agreement between the pollutographs was satisfactory. The loads calculated in Thales and E2 are shown in **Table 5** and the EMC and DWC values are presented in **Table 6**. The total loads calculated do not differ by more than 5% for any constituent with the exception of salt for Soil A where the loads differ by 15%.

**Table 5**: Total Loads exported for salt and phosphorus in Thales and E2 simulation

| Case | Total Salt (kg/yr) Thales | Total Salt (kg/yr) E2 | TP (kg/yr) Thales | TP (kg/yr) E2 |
|---|---|---|---|---|
| A | 3.76 | 3.21 | 0.05 | 0.048 |
| B | 166.5 | 165.9 | 0.452 | 0.45 |
| C | 506.6 | 481.7 | 1.29 | 1.33 |

**Table 6**: Calibrated EMC and DWC for soils A, B and C

| Case | Phosphorus | | Salt | |
|---|---|---|---|---|
| | DWC | EMC | DWC | EMC |
| A | 0.04 | 0.045 | 2.7 | 3 |
| B | 0.16 | 1 | 60 | 100 |
| C | 0.4 | 0.5 | 145 | 160 |

## 3. RESULTS

### 3.1. Soils with different runoff processes

This case used soil types A (saturation excess dominated) and B (subsurface flow dominated) in E2 and Thales simulations. The different hydrographs obtained for Thales cases AB, BA and E2 are shown in **Figure 2** and the associated phosphorus pollutograph are in **Figure 4**. Here the first letter indicates which soil unit is located on the upslopes. The total load exported and runoff coefficients are shown in **Table 7**.

When soil B is on the lower slopes, the results for Thales and E2 have a similar shape (compare the red and blue lines). This behaviour is due to the fact that catchment B generates much of the runoff in E2 and is the controlling catchment in Thales as it is located at the bottom. As E2 does not recognize the interaction between the two catchments and the inflow of phosphorus rich water from catchment A, it underestimates the phosphorus export by 7% and of salt by 10%.

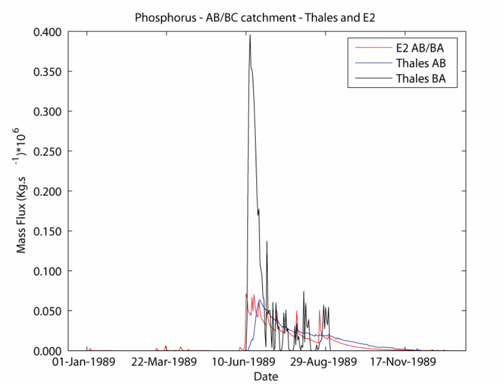


**Figure 4**: Phosphorus pollutographs for the AB/BA.

**Table 7**: Runoff coefficient, total salt and total phosphorus export for the AB/BA catchment

| Case | Runoff Coefficient | Total Salt (kg) | Total P (kg) |
|---|---|---|---|
| Thales AB | 0.097 | 94.4 | 0.26 |
| Thales BA | 0.105 | 102.4 | 0.46 |
| E2 AB/BAC | 0.092 | 84.6 | 0.24 |

When the soil A is located at the bottom, its low hydraulic conductivity generates a hydrograph that is more "flashy", behaviour not present in the E2 simulations. In Thales, soil A has a higher concentration of phosphorus and salt, and as a result of the different hydrographs the exported amount predicted by the E2 model is underestimated by 17% for salt and 47% for phosphorus.

The comparison between these simulations demonstrates the importance of landscape connectivity. Changes in flow and constituent export patterns caused by the landscape interaction are clear for the Thales simulations. While E2 can predict the behaviour of each separate soil, it cannot simulate the interaction between the two soils in the configuration used here. Water rich (poor) in nutrients from one sub catchment interacts with water poor (rich) in nutrients from the other sub catchment. The final results are quite different than a simple sum of the flow and associated loads.

### 3.2. Soils with same processes

The different hydrographs and associated phosphorus pollutographs obtained for E2 and

Thales cases BC and CB are shown in **Figure 5** and **Figure 6** respectively (salt not shown), where the first letter indicates which soil unit is upslope. The exported load and runoff coefficients are shown in **Table 8**.

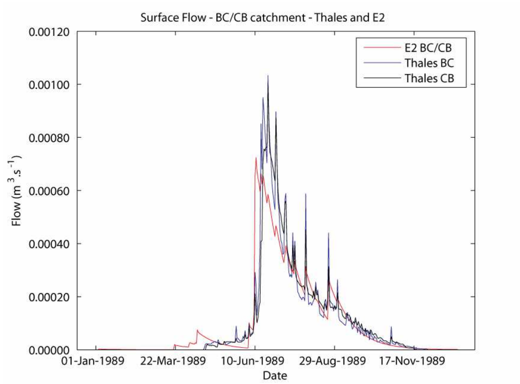


**Figure 5**: Hydrographs for the BC/CB catchment.

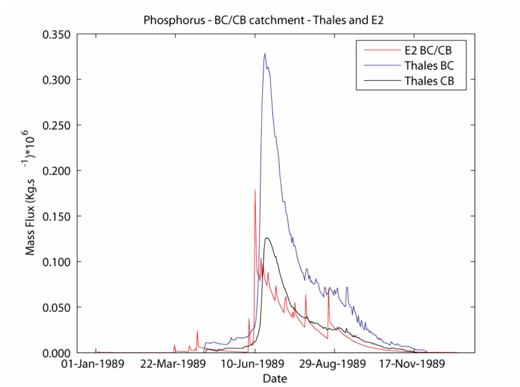


**Figure 6**: Phosphorus pollutographs for the BC/CB.

**Table 8**: Runoff Coefficient, total salt and total phosphorus export for the BC/CB catchment

| Case | Runoff Coefficient | Total Salt (kg) | TP (kg) |
|---|---|---|---|
| Thales BC | 0.16 | 401.7 | 1.21 |
| Thales CB | 0.16 | 249.5 | 0.48 |
| E2 BC/CB | 0.146 | 335.1 | 0.43 |
| E2 BC/CB Calib[1] | 0.154 | 338 | 0.447 |

1-Flows calibrated against the Thales BC hydrograph.

The Thales hydrographs show similar results for the two cases. However, when soil B (higher conductivity, 50% lower constituent concentration) is on the lower slopes, the total load of constituents exported is much smaller than when soil C is on the lower slopes. When the soil with higher concentrations is at the bottom, the loads exported are around 61 and 120% higher for salt and phosphorus respectively, due to local influence of constituent rich soils. These differences are not present in E2 since the interaction between the two soil units is not considered.

It could be argued that the different loads exported are due to differences in the hydrographs between E2 and Thales and that in practice, if the whole catchment hydrograph is known, the flows in E2 can be calibrated to improve the constituent export estimate. To evaluate this strategy, a second E2 model was calibrated to reproduce the hydrograph of the Thales BC case. As shown in **Table 8**, the changes for salt and phosphorus are not significant, showing minor improvement.

These changes in the load exported are explained by the EMC/DWC values shown in **Table 6**. The new calibration produces more flow but does not change the amount of baseflow significantly. The increase in runoff accounts for the increase in total loads exported, but the absence of localised effects still places significant errors in the load estimation.

## 4. CONCLUSIONS AND RECOMENDATIONS

Comparison between hydrographs and associated nutrient loads for a spatially explicit and a lumped model highlight the importance of considering catchment connectivity and spatial location. Water inflow from one sub catchment to the next can increase/decrease the leaching of solutes. In the inverse case, runoff from a low conductivity area may be trapped by a soil with larger conductivity and storage capacity therefore reducing the exported load. Lumped models that disregard these interactions can significantly over or under predict nutrient export.

As differences in soil properties and constituent concentrations between sub catchments becomes more heterogeneous, the more important is the consideration of the interaction between the landscape units. This has important implications for modelling the impact of management interventions that are targeted with landscape position in mind.

Given the tension between these results and the difficulty in routinely applying detailed spatially explicit models, it is imperative to find solutions that account for the connectivity of the catchment in a parsimonious manner. This would retain the advantages of lumped models such as short run times and simplicity while achieving greater realism by considering spatial connectivity. Furthermore, whilst this study is a comparison between modelling approaches, it is important to validate these finding against independent data.

## 5. ACKNOWLEDGMENTS

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