Modelling of water, sediment and phosphorus runoff: implications for grain cropping in southwest Australia

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Abstract
Fertiliser decision support systems are widely used for making phosphorus (P) fertiliser recommendations. However, the current decision support systems do not provide an environmental assessment (e.g. P runoff) of the P fertiliser recommendation. This paper outlines the three modelling components required for fertiliser decision support systems to predict P runoff. The first component considers water runoff and is directed at calculating runoff volume (Q_{surf}) and peak runoff rate (q_{peak}). The second component makes predictions of soil erosion, sediment yield (SED), using the modified universal soil loss equation (MUSLE). Runoff volume and peak runoff rate predictions are used in the second component to calculate sediment yield. The third component makes predictions of P runoff by calculating the amount of dissolved and particulate P runoff. Dissolved P runoff is calculated using runoff volume and the water soluble P contents of the soil, fertiliser and manures. Particulate P runoff is calculated using runoff volume, sediment yield and total P content of the soil, fertiliser and manure. Total annual P runoff is the sum of dissolved and particulate P runoff for each individual water runoff event. It is argued that all three components are required for a decision support system to accurately predict P runoff. The implications of this approach are considered for grain cropping areas in the mediterranean climate of southwest Australia.

Key Words
Phosphorus, water, sediment, runoff, modelling.

Introduction
When the land was first cleared in the southwest of Australia, the soils were very deficient in P (Wild 1958). Deficiency was corrected by the application of P fertilisers to the extent that most current P fertilisers are applied at a rate which maintain the P supply in soils. Current practices have been achieved by conducting soil test measurements for P and the use of P fertiliser decision support systems for making P recommendations. In general, this approach has resulted in the efficient use of P fertiliser. However, in some coastal agricultural areas of the region, over-use of P fertiliser has resulted in eutrophication of estuarine waters. In a recent review, Mathers *et al.* (2007) has highlighted the potential for P loss from the adoption of increased frequency of cropping in the high rainfall, greater than 550 mm of annual rainfall, zone of Australia. Minimal tillage with crop residue retention (conservation farming) has been widely adopted within Australia. This practice has the potential to reduce soil bound P loss (Particulate P) but can result in an increase in dissolved P loss due to the surface concentration of nutrients. As a result, agriculture is under increasing pressure to develop management practices which will minimise P loss from agricultural lands. Currently P decision support systems do not have routines for making predictions of P runoff to the environment. Hence, the aim of this paper is to outline the P environmental routines required for fertiliser decision support systems to accurately predict P runoff from grain cropping land in southwest Australia.

Model components
P runoff from agricultural lands is generally derived from a small part of the landscape during a few relatively large rainfall events when these areas have high soil P or have received a recent application of P fertiliser or manure (Weld and Sharpley 2007). Calculation of P losses to the environment requires the use of three modelling components. First, water runoff is modelled to calculate runoff volume (Q_{surf}) and peak runoff rate (q_{peak}). Second, runoff volume and peak runoff rate are used in MUSLE to calculate sediment yield (*SED*). Third, runoff volume, peak runoff rate and sediment yield (*SED*) are used by the P runoff

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component to calculate daily dissolved and particulate P runoff. Total annual P runoff is then calculated as the sum of dissolved P and particulate P runoff for each individual water runoff event.

Runoff volume

Runoff volume (Q_{surf}) is the total amount of rainfall minus infiltration and interception. It is calculated using the Soil Conservation Service (SCS) curve number (CN) method (SCS 1972). Curve number is a function of the hydrologic soil group, surface cover (crop residues and vegetation) cultural practices of the site and the antecedent soil moisture conditions. The curve number ranges from 1 to 100, with runoff potential increasing with increasing curve number. The curve number method calculates runoff volume using daily rainfall using the following equation:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{R_{day} + 0.8S} \quad (1)$$

where R_{day} is daily rainfall (mm) and S is the retention parameter (mm).

The retention parameter is defined as follows;

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (2)$$

where, CN is the curve number for the day. Rainfall (R_{day}) must be greater than 0.2S, referred to as initial abstraction, for the equation to be applicable.

Peak runoff

Peak runoff (q_{peak}), is predicted based on a modification to the rational formula of Hann *et al.* (1994). The rational formula method is based on the assumption that if a rainfall of intensity, I, begins at time t=0 and continues indefinitely, then the rate of runoff will increase until the time of concentration (t_{conc}) when the entire sub-basin area is contributing to the flow at the outlet. The rational formula is given by the following equation:

$$q_{peak} = \frac{\alpha_{tc}\, Q_{surf}\, Area}{3.6\, t_{conc}} \quad (3)$$

where q_{peak} is the peak runoff rate (m^3/s), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is runoff volume (mm), Area is the sub-basin area (km^2), t_{conc} is the time of concentration for the sub-basin (hr) and 3.6 is a unit conversion factor.

Sediment runoff

Sediment runoff is modelled using MUSLE (Pandey *et al.* 2009):

$$SED = 11.8(Q_{surf}\, q_{peak}\, area_{hru})^{0.56}\, K\; C\; P\; LS\; C_{frg} \quad (4)$$

where *SED* is the sediment yield on a given day (t), Q_{surf} is runoff volume (mm), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the hydrologic response unit (ha), *K* is the soil erodibility factor, *C* is the cover and management factor (dimensionless), *P* is the erosion control practices factor (dimensionless), *LS* is the topographic factor (alternatively, *L* is the slope length factor (dimensionless) and *S* is the slope steepness factor (dimensionless)), and C_{frg} (dimensionless) is the coarse fragment factor.

(1) **Soil erodibility factor (K)**, is soil erosion rate of a specified soil under continuous fallow having a 9 % slope and 22.1 m length. It is calculated by:

$$K = 2.77M^{1.14}(10^{-7})(12 - OM) + 4.28(10^{-3})(c_{soilstr} - 2) + 3.29(10^{-3})(c_{perm} - 3) \quad (5)$$

where *M* is the particle-size parameter, *OM* is the percent organic matter (%), $c_{soilstr}$ is the soil structure code used in soil classification and c_{perm} is the profile permeability class (Loch *et al.* 1998).

(2) **Cover and management factor (C)**, is the ratio of soil loss from a field with a specified cropping and management to that from the fallow condition for which *K* is determined. It is calculated daily using the following equation:

$$C = \exp([\ln(0.8) - \ln(C_{mn,j})]\exp[-1.15CV] + \ln[C_{mn,j}]) \quad (6)$$

where $C_{mn,j}$ is the minimum value of the crop management factor for crop *j* and *CV* is the soil cover (above ground biomass plus residue) in kg/ha.

(3) **Support practice factor (P)**, is defined as the ratio of soil loss with a specific support practice to the

corresponding loss with up-and-down slope culture. Support practices include contour tillage, strip cropping on the contour, and terrace systems. Stabilized waterways for the disposal of excess rainfall are a necessary part of each of these practices.

(4) **Topographic factor (LS)**, is the expected ratio of soil loss per unit area from a field slope to that from a 22.1 m length of uniform 9 % slope under otherwise identical conditions.

(5) **Coarse fragment factor (C_{frg})**, accounts for the percent rock in the first layer (%).

Phosphorus runoff

The transfer of soil P to runoff water is controlled by the physical and chemical processes such as desorption, dissolution and diffusion. P originating from the soil can be transported in runoff water either dissolved in solution (dissolved P, DP) or associated with eroded soil particles (particulate P, PP). The portion of total P transported as PP varies widely and depends on soil type, degree of P saturation, particle size and management history (Sharpley 1993). However, recent studies in southwest Australia suggest that throughflow is the major process of water and P lateral flux on hillslopes, especially on duplex profiles (McKergow *et al.* 2006; Sharma 2009).

(1) **Dissolved P** which includes inorganic (DP_i) and organic (DP_o) in runoff is directly related to the quantity and reactivity of P near the soil surface (McDowell and Sharpley 2001). Sharpley *et al.* (2002) have defined a relationship between P soil test (Mehlich-3) and dissolved P concentration in runoff. In Western Australia, the Colwell (1963) method is used as the soil P test with a sampling depth of 10 cm. Bolland *et al.* (2003) has shown that Colwell (1963) P soil test is highly correlated to Mehlich-3 P for soil treated with single super phosphate. Hence, the Colwell P soil test values can be directly substituted into the McDowell and Sharpley (2001) relationship. The relationship is described by the following equation.

$$DP_i = extraction\ coefficient \times available\ soil\ P \times Q_{surf} \quad (7)$$

where DP_i is dissolved P loss in overland flow (kg P/ha), available soil P or soil test for P is the amount of P in a unit depth of surface soil, usually 5 cm (kg/ha) and extraction coefficient is the fraction of soil test P that can be released to a given runoff volume. Extraction coefficients can be determined as the slope of the linear regression of soil test P and overland flow dissolved P. For Western Australian conditions, the impact of the different soil sampling depths needs to be assessed. Initial results for a range of soils of the Fitzgerald River basin in the south coast region of Western Australia showed that Colwell P was twice as high in the 0-2 cm depth as in the standard 0-10 cm sampling depth (Sharma 2009). Sharma (2009) also showed that the dissolved organic P (DP_o) fraction comprised a large proportion of the total DP in runoff, throughflow and leachate.

(2) **Particulate P** which includes inorganic (PP_i) and organic (PP_o) P attached to soil particles may be transported by surface runoff. The concentration of P per unit mass of eroded particles is related to the total P concentration of the soil. When compared to the soil, the concentration of total P in eroded soil particles is higher because the erosion process selects the more easily transported soil particles such as clay and low density organic particles (Sharpley 1985). These particles have a higher sorption capacity for P than the bulk soil. The increased P concentration in eroded soil particles relative to the bulk soil is called the P enrichment ratio (PER). Enrichment ratios are used to represent the increase in P concentration of sediment relative to the parent soils.

Menzel (1980) showed that for a wide range of soil vegetative conditions, P enrichment ratio is predicted using a logarithmic relationship.

$$Ln(PER) = 2.00 - 0.16\ Ln\ (SED) \quad (8)$$

where *SED* is sediment discharge in kg/ha.

Most nonpoint source models have adopted this approach to predict particulate P transport in overland flow. This relationship is based on the well documented observation that particulate P loss increases as erosion increases. P enrichment ratio decreases with increased erosion. As erosion increases, there is less particle size sorting by overland flow, less clay-sized particles are transported in proportion to total soil loss and therefore P enrichment decreases.

Once an appropriate P enrichment ratio is obtained from sediment discharge, particulate P loss can be calculated as;

$$PP = TP \times SED \times PER \times Q_{surf} \quad (9)$$

where PP is particulate P loss in overland flow (kg/ha), TP is total soil P in a unit depth of surface soil, SED is sediment concentration (g sediment/L) in overland flow and PER is P enrichment ratio calculated using Equation 8, for a given flow event volume (cm).

Conclusion

Modelling P runoff is a complex process. It requires the use of three interacting modelling components. These include a water runoff (volume and peak rate) component, a soil erosion or sediment yield component and finally a P runoff component. Work is currently progressing in developing and evaluating these modelling components for predicting P losses from grain cropping land in the southwest of Australia. Preliminary field results suggest that the PP fraction may not be a major form of P loss and that greater understanding of the DP_o fraction is needed to predict P losses from grain cropping land in southwest Australia.

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