Proposed Updates to the Soil and Water Assessment Tool (SWAT) Phosphorus Model

White M., D. Storm, H. Zhang, C. Penn, P. Busteed, G. Fox , and M. Smolen

Departments of Biosystems and Agricultural Engineering and Plant and Soil Sciences

Division of Agricultural Sciences and Natural Resources, Oklahoma State University

Abstract

The Soil and Water Assessment Tool (SWAT) model has been used extensively across the US and Europe to predict Phosphorus (P) loads originating from large mixed land use watersheds. The P routines in SWAT originate from Erosion and Productivity Impact Calculator (EPIC), a field scale model. Both models have demonstrated the ability to predict P loads originating from agricultural areas with reasonable accuracy throughout the literature. There is, however, room for improvement. The P routines in SWAT and EPIC were developed in early 1980's and have changed very little since, even though the body of research concerning P has expanded tremendously. Other researchers have proposed significant updates to better represent manure application in model like SWAT, but it is not known when these will be included. This research will focus on changing static coefficients in the SWAT model to dynamics coefficients, modifying manure applications to account for alum amendment, and other relatively easy modifications.

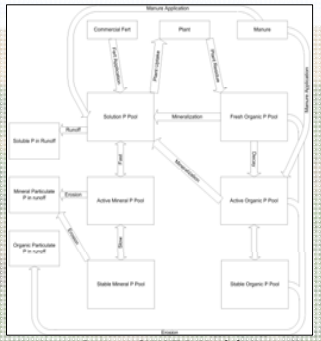
The Soil and Water Assessment Tool

SWAT (Arnold et al., 1996) is a basin scale model developed by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas. SWAT is a comprehensive model designed to predict nitrogen, phosphorus (P), pesticide, and sediment losses, runoff, evapotranspiration, and crop growth. The model allows management and Best Management Practices (BMP) to be evaluated. SWAT is a widely accepted model which has been used extensively by hydrologists and engineers since 1994. The field scale routines of the SWAT model are derived from the Erosion and Productivity Impact Calculator (EPIC) (Williams et al., 1984). SWAT and EPIC have been widely used in both the United States and Europe and are accepted tools for the quantification of environmental concerns such as P.

Prior to calibration, SWAT has a tendency to over predict P loss in fields receiving large amounts of P fertilizers. Model calibration can remove this systematic bias, and after model calibration SWAT predictions generally are quite good. Improvement in the SWAT P subroutines should reduce the need for model calibration in these applications.

SWAT Phosphorus Model

The SWAT P model is virtually identical to that in EPIC, both are based on the concept of separate P pools within each soil layer. SWAT partitions soil P in six pools, three intended to represent mineral P forms and three for organic forms. The three mineral pools are *Stable*, *Active* and *Solution*. These pools are in a dynamic equilibrium based on constant ratios. The organic pools are *Stable*, *Active* and *Fresh*. Transformations between these pools are based on mineralization, decomposition, and immobilization equations and will not be modified in this research. It should be noted that there tends to be some confusion as to what forms of P are in each pool.



Current SWAT P Model

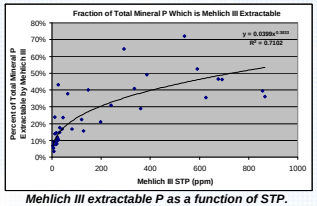
Stable Mineral Pool - Represents stable insoluble P forms not readily available for plant uptake. The stable mineral pool reaches equilibrium very slowly with the *Active* pool, and by default is four times larger than the *Active* pool. This is the largest of the mineral P pools.

Active Mineral Pool - Interacts slowly with the *Stable* pool and quickly with the *Solution* pool. This pool represents P which is reversibly precipitated or adsorbed, but is less active than *Solution* P. By default this pool is 1.5 times larger than the *Solution* pool.

Solution Pool - Includes soluble mineral P in soil solution, and P which can easily become soluble. Plant P uptake, soluble P in surface runoff, and P leaching are taken from this pool. Mineralized organic matter P and inorganic fertilizer P enter this pool. The initial value for this pool is a user defined concentration. The initial *Solution* pool value, which is an input, sets both the active and stable P pools via fixed ratios. Note that sometimes this *Solution* pool is known as the labile pool.

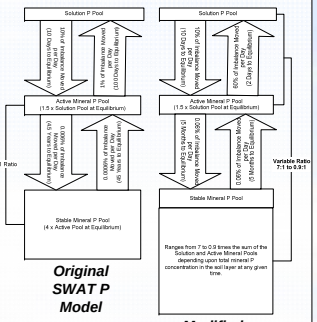
Redefining Phosphorus Pool Equilibriums

SWAT uses fixed ratios to define the equilibrium between the *Solution*, *Active*, and *Stable* mineral pools. We propose to alter the fixed ratio between the *Active* and *Stable* mineral P pools (currently 1:4) to a dynamic coefficient based on Soil Test P (STP). We derived a relationship between Mehlich III STP and the total mineral soil P using data presented by Sharpley et al. (2004), shown in the figure to the right. These data indicate that as STP increases, the fraction of the total mineral P within the soil extracted by Mehlich III increases in a nonlinear way. This also implies that the amount of fertilizer required to raise STP by one unit is higher at low initial STP than at a higher STP. These data contain a variety of soils at varying STPs; some have a long term history of manure application. Other studies support a nonlinear relationship between STP and the total soil P. Pautler and Sims (2000) found a relationship between total P and STP, which appears to be nonlinear. Allen (2004) found higher STP to total P ratios at higher STP levels. Whalen and Chang (2001) observed a STP to total P ratio of 0.13 in plots with no manure application and a ratio of 0.27 in a soil with long term additions of manure.



Mehlich III extractable P as a function of STP. Data from Sharpley et al. (2004)

The STP extractability relationship based on Sharpley et al. (2004) data was used to allow STP to be a direct SWAT input. The STP fraction was assumed to be the sum of the *Soluble* and *Active* mineral P pools. The existing equilibrium relationship between the *Stable* and *Active* pools was modified to an equilibrium relationship between the *Stable* pool and the sum of *Active* and *Solution* pools. The new equilibrium ratio varies between 7 at low STP to 0.9 at high STP.



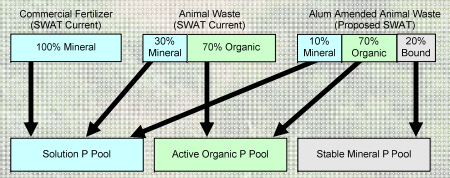
Original SWAT P Model

Modified SWAT P Model

Alum Amended Manures

The addition of aluminum (i.e. alum), iron or calcium containing amendments to animal manures have been shown to reduce the solubility of P in the wastes. When amended wastes are applied to agricultural fields, soluble runoff P concentrations are reduced compared to unamended manures. In an effort to account for reduced solubility of P in treated manures, the SWAT model was modified to allow the addition of stable P forms in animal wastes which do not directly influence soluble P in surface runoff.

The SWAT model assumes animal wastes are composed of relatively soluble mineral and readily degradable organic forms. These are directed to the *Solution* and *Fresh Organic* pools upon application. The addition of alum reduced water soluble P in manures by 66% in farm scale data collected by Sims and Luka-McCafferty (2002). Other researchers have published similar results (Moore and Miller, 1994). In an effort to better represent the reduced P solubility in alum treated manures the SWAT model was modified to allow manure P to be further subdivided into soluble mineral, organic, and stable mineral forms. The new stable mineral fraction is directed to the *Stable* soil pool upon application and will not immediately increase STP within the model, however the total soil P will still increase. The application of alum treated litter results in smaller increases in STP as compared to normal litter (Moore et al., 1999). These modifications should allow SWAT to better account for this important BMP.



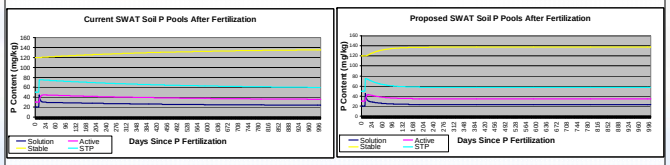
SWAT Fertilizer Routine Modifications

Rate of Phosphorus Transformation

SWAT uses fixed rate constants to move a fraction of the imbalance between the *Solution*, *Active*, and *Stable* P pools. Ten percent (0.10) of the imbalance between the *Solution* and the *Active* pools is moved per day when the imbalance favors movement from *Solution* to *Active* (sorption). One percent (0.01) is moved if the imbalance favors movement from *Active* to *Solution* (desorption). Vadas et al. (2006) developed dynamic coefficients for *Solution* and *Active* pool interactions. Vadas et al. (2006) also presented static coefficients (0.10 for sorption, 0.60 for desorption) which improved EPIC mode predictions. These static coefficients were incorporated into the modified SWAT model.

P transfer between the *Active* and *Stable* P pools was also updated. SWAT uses a relatively slow coefficient, only 0.006% (or 0.0006% depending upon direction) of the imbalance between the *Active* and *Stable* pools transfer per day. About 90% of excess P in the *Active* pool is moved to the *Stable* pool in four years. These rate constants are based on Jones et al. (1984) and Cox et al. (1981). These studies used the decline in extractable P following fertilization over several years to define the rate constants. It is difficult to separate the effects of P stabilization and transformation to less available forms and net P loss through crop uptake and runoff. All of these mechanisms should slowly reduce extractable P over time.

Soil incubation studies are not subject to losses which complicate these field studies. Laboski and Lamb (2003) measured STP in soils incubated for nine months after receiving manure and inorganic P. STP changed significantly only during the first month after manure application in the majority of soils. They observed a relative small (<3%) decrease in adjusted STP after inorganic P fertilization between months one and nine. Ebeling et al. (2003) incubated a silt-loam receiving various P application rates for 64 weeks. STP stabilized after 16 weeks of incubation except at very high rates. Koopmans et al. (2004) found strong indications that the total pool of sorbed P (sum of reversibly adsorbed P and quasi-irreversibly bound P) to be close to equilibrium with the faster reacting P in a long term P uptake study. These studies suggest that the transfer between the active and stable pools to regain equilibrium is faster than the current SWAT routines allow. Little data are available to gage the appropriate value for the *Active/Stable* transfer coefficient. A value of 0.006 (one order of magnitude greater than the original coefficient) will be evaluated as a replacement coefficient.



Change in Stable, Active and Solution P pools after Fertilization Using Original (Left) and Modified (Right) SWAT Transfer Coefficients

Conclusions

SWAT and EPIC are the result of many years of development by talented researchers. The SWAT model in its original form does a good job of predicting P loss in manured fields areas after calibration. Models like SWAT and EPIC have been used successfully in these situations for years. However, there is room for improvement, especially when models are uncalibrated. We currently have data available to develop better process based P models. Our models are on the right track, but the older P routines do not represent our current state of knowledge. Model developers have been slow to incorporate information from the P researchers. However, in order to properly utilize this new information, both the model developers and P researchers must work together. Given the widespread use of these models, it is important that they contain the best possible algorithms. The changes suggested in this research are relatively minor and easy to implement. A version of SWAT including these changes is being tested by Oklahoma State University and will be incorporated into a SWAT based P index. These changes can be incorporated with changes suggested by other researchers to build more realistic P models.

References

1. Allen, B., 2004, Soil and Runoff Phosphorus as Affected by Fertilizer and Manure Application. PhD. Dissertation, Iowa State University
2. Cox, F., E. Kamprath and R. McCollum, 1981, A Descriptive Model of Soil Test Nutrient Levels Following Fertilization., Soil Sci Soc. 45:529-532
3. Ebeling, A., L. Cooperband, and L. Bundy, 2003, Phosphorus Source Effects on Soil Test Phosphorus and Forms of Phosphorus in Soil, Communications in Soil Science and Plant Analysis 34:1897–1917
4. Jones, C., C. Cole. A. Sharpley, and J. Williams 1984. A Simplified Soil and Plant Phosphorus Model. I. Documentation.. Soil Science Society of America Journal 48:800-805
5. Koopmans, G.; W. Chardon, P. Ehlert, J. Dolfing, R. Suurs, O. Oenema, and W. Riemsdijk, 2004, Phosphorus Availability for Plant Uptake in a Phosphorus-Enriched Noncalcareous Sandy Soil. , J. Environ. Qual. 33:965–975
6. Moore, P. and D. Miller., 1994, Decreasing Phosphorus Solubility in Poultry Litter with Aluminum, Calcium, and Iron Amendments., J. Environ. Qual. 23:325-330
7. Moore, P., T. Daniels, and D. Edwards, 1999, Reducing Phosphorus Runoff and Improving Poultry Production with Alum journal of Poultry Science 78:692–698
8. Pautler , M. and T Sims, 2000, Relationships Between Soil Test Phosphorus, Soluble Phosphorus, and Phosphorus Saturation in Delaware Soils., Soil Sci. Soc. Am. J. 64:765–773
9. Sharpley, A., R. McDowell, P Kleinman, 2004, Amounts, Forms and Solubility of Phosphorus in Soils Receiving Manure. Soil Science Society of America Journal., 68:2048
10. Sims, J., and N. Luka-McCafferty 2002, On-Farm Evaluation of Aluminum Sulfate (Alum) as a Poultry Litter Amendment: Effects on Litter Properties J. Environ. Qual. 31:2066–2073
11. Whalen, J and C. Chang, 2001, Phosphorus Accumulation in Cultivated Soils from Long-Term Annual Applications of Cattle Feedlot Manure J. Environ. Qual. 30:229-237