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PREDICTION OF RUNOFF AND SEDIMENT FROM AGRICULTURAL WATERSHEDS BY A MATHEMATICAL MODEL. III

SEDIMENT-BOUND AND SOLUBLE PHOSPHORUS LOADINGS.

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ABSTRACT

Eutrophication or the enrichment of waters by nutrients, particularly phosphorus, has become a serious problem in the United States. Models are extremely useful for planning the reduction of eutrophication and other water quality problems. A phosphorus transport component was added to ANSWERS, a distributed parameter model which has already been demonstrated to model runoff and sediment transport with different degrees of success. Only sediment-bound and soluble phosphorus transport were considered here. In predicting sediment-bound phosphorus, a negative logarithmic equation was derived for the phosphorus, enrichment ratio using data from the Black Creek project area. For soluble phosphorus, an empirical relationship was used between Bray-P_1 and desorbed soluble phosphorus at different water:soil ratios.

Simulations of small experimental watersheds show that the phosphorus transport component is useful for the prediction of sediment-bound and soluble phosphorus loadings transported to the rivers and lakes for a wide variety of input conditions.

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برآورد سیلاب و رسوب از حوزه‌های آبخیز کشاورزی با استفاده از یک‌مدل ریاضی ۳: بارهای فسفر همراه با ذرات و محلول

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چکیده:

اضافه شدن مواد غذائی گیاهی خصوصاً فسفر به آب (Eutrophication) مسأله جدی و مهمی در آلودگی آبها در ایالات متحده شده‌است. مدلهای ریاضی جهت کاهش (Eutrophication) وسایر مسائل مربوط به کیفیت آب بسیار مفید هستند. جهت بررسی انتقال فسفر از زمین‌های کشاورزی قسمت جدیدی که مدل حرکت فسفر از زمین های مذکور است به مدل ANSWERS اضافه شد. مدل ANSWERS که یك مدل Distributed می باشد قبلاً از نظر هیدرولوژی و فرسایش خاك از حوزه‌های آبخیز مختلف کارآئی خود را نشان داده است. بعلت پیچیدگی چرخه فسفر در طبیعت فقط انتقال فسفر چسبیده به ذرات کلوئیدی فرسایش یافته از سطح خاك حوزه آبخیز (Sediment-bound phosphorus) و فسفر محلول (Soluble phosphorus) در سیلاب در مدل پیشنهادی مورد نظر بوده‌اند.

در مورد انتقال فسفر انتقال یافته همراه ذرات معلق از معادله‌ای لگاریتمی که رابطه بین فسفر موجود در ذرات فرسایش یافته و مواد معلق را نشان میدادند استفاده شده‌است. این معادله بر اساس اطلاعات و ارقام حاصله از چندین سال پژوهش در حوزه Black Creek بدست آمده‌است. برای انتقال فسفر محلول ازیك رابطه تجربی که بین فسفر قابل استفاده (Bray-P$_1$) و فسفر محلول در نسبت های مختلف آب وخاك بدست آمده بود استفاده‌شد.

نتایج شبیه سازی حوزه‌های آبخیز کوچك مورد مطالعه نشان دادند که مدل پیشنهادی برای پیش بینی انتقال فسفر از زمین‌های کشاورزی به آبهای سطحی نظیر رودخانه‌ها و دریاچه‌ها به شکل فسفر چسبیده به ذرات فرسایش یافته خاك و محلول در آب می تواند مورد استفاده قرار گیرد.

INTRODUCTION

Soil nutrients are sources of nonpoint pollutants that can affect water quality. Phosphorus has been the object of concern because of its role in the eutrophication process. Phosphorus is generally bounded to soil particles, both directly in a sediment-bound mode, and indirectly through sorption-desorption reactions. In addition to sediment-bound phosphorus, another important mode of transport of phosphorus is through runoff and stream flow as soluble phosphorus. This form of phosphorus is readily available for aquatic growth.

METHOD OF APPROACH

The pathway by which phosphorus moves from agricultural lands to receiving waters are shown in Fig. 1. The development of a phosphorus transport model here consists of simulating the sediment-bound phosphorus contributing to water bodies through the erosion/sedimentation process for a single storm event. Also we simulate the soluble phosphorus movement in surface runoff for single storm events. The remaining processes of Fig. 1 are ignored.

Since soil erosion is a process selective with respect to particle size, runoff is usually richer in fine particles and organic matter than the surface soil from which the eroded soil comes (4). This selective erosion of fine particles occurs because they are eroded and transported more easily than the coarse particles. In addition, larger particles tend to be deposited first, due to their higher settling velocities. As a result, eroded soil usually has a higher concentration of nutrients, due to higher ion exchange capacity of clay and fines. This nutrient enrichment can be expressed as an enrichment ratio, which is the concentration of the nutrient in the eroded material, divided by the concentration of the nutrient in the original soil mass. Thus the phosphorus enrichment ratio must be taken into account in the loading of sediment-bound phosphorus transported by surface runoff

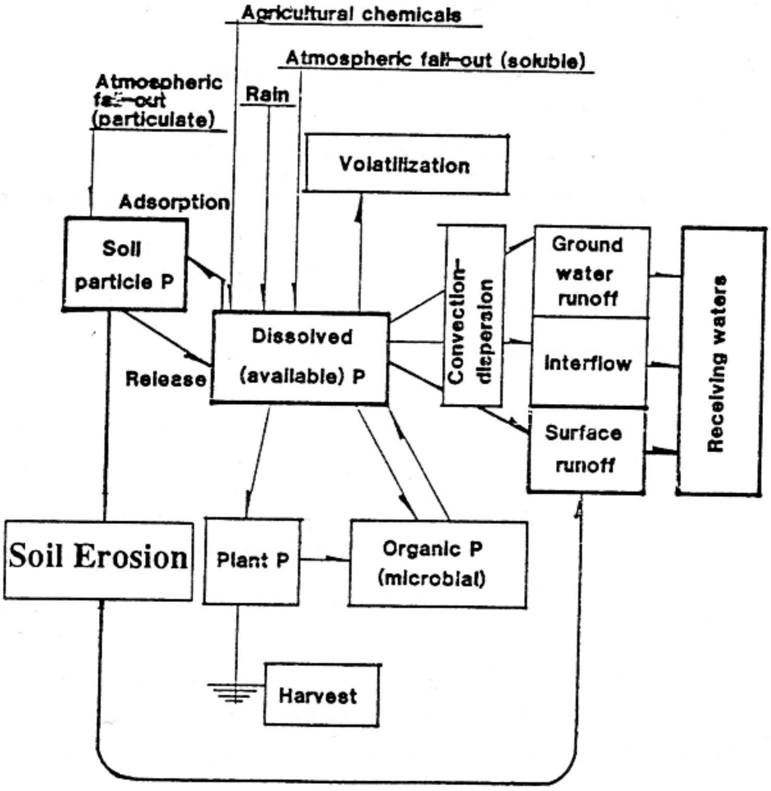

Fig. 1. Soil Phosphorus interactions and transport routes to receiving water.(Modified from Novotny,and Trans, 1978).

from a watershed. The value of phosphorus enrichment ratio is reported to be between 1 to 3.5 (4,10) and 2.1 to 6.5 (8). However, after several years of study on Black Creek watershed, Nelson et al. (5) reported a range of 2.5 to 6.4 for this ratio. In the Black Creek watershed, data from several years of experimentation have shown the following relationship:

$$\ln PER = 2.48 - 0.21 * \ln (SS) \qquad [1]$$

where,

PER = P-enrichment ratio
SS = sediment in suspension, ppm

Fig. 2 shows the relationship of the PER, and sediment concentration.

Römkens and Nelson (7) showed experimentally that desorbed phosphorus was a function of Bray-P_1 at equilibrium. In this study the desorbed phosphorus was determined in the laboratory for different water:soil ratios. Fig. 3 shows isotherm lines for 25, 250, 500 water:soil ratios for Fincastle silt loam taken from Stafford watershed located southwest of Indianapolis, Indiana, USA. The equation which governs the relationship between desorbed phosphorus and Bray-P_1 is :

$$P_s = K(WS)^a (BPL)^\beta \qquad [2]$$

where,

P_s = desorbed phosphorus, $\mu g\ g^{-1}$ of soil
K = desorbed phosphorus at the axis intercept, $\mu g\ g^{-1}$
WS = water:soil ratio
BPL = soil Bray-P_1 phosphorus, $\mu g\ g^{-1}$ soil
a,β = constants depending on soil type.

During simulation of a storm event, the volume of runoff and sediments in suspension is calculated by the ANSWERS model for each element. The water:soil ratio thus can be predicted and Bray-P_1 is measured in the laboratory for each soil type. So if K, a, and β for each soil of the watershed are known, then the input data file for watershed will contain the soil parameters information involving soluble phosphorus transport (Fig. 4). Consequently, the P_s, desorbed phosphorus, can be calculated for each element, and finally for the whole watershed.

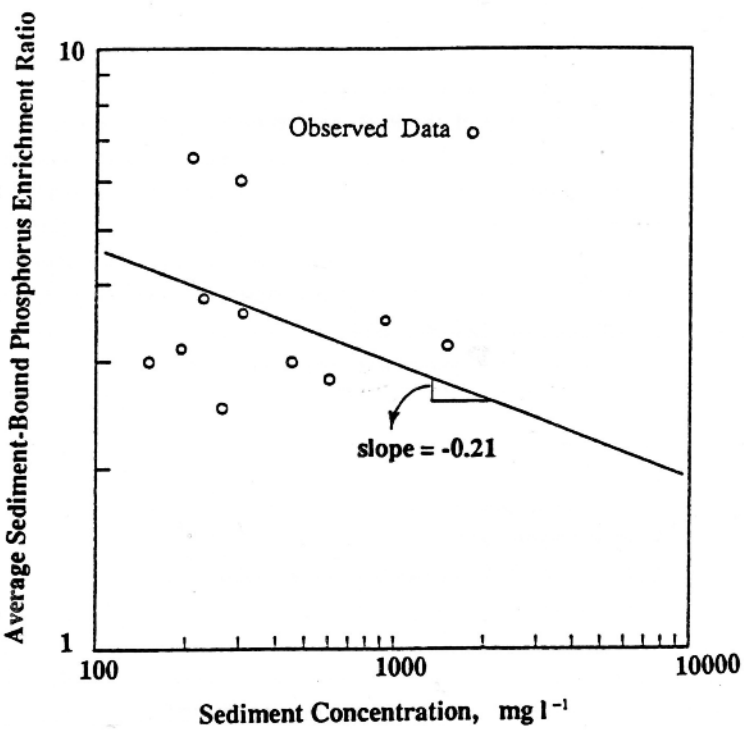

Fig. 2. Relation between sediment concentration in the outflow and the sediment-bound phosphorus enrichment ratio for the Black Creek watershed.

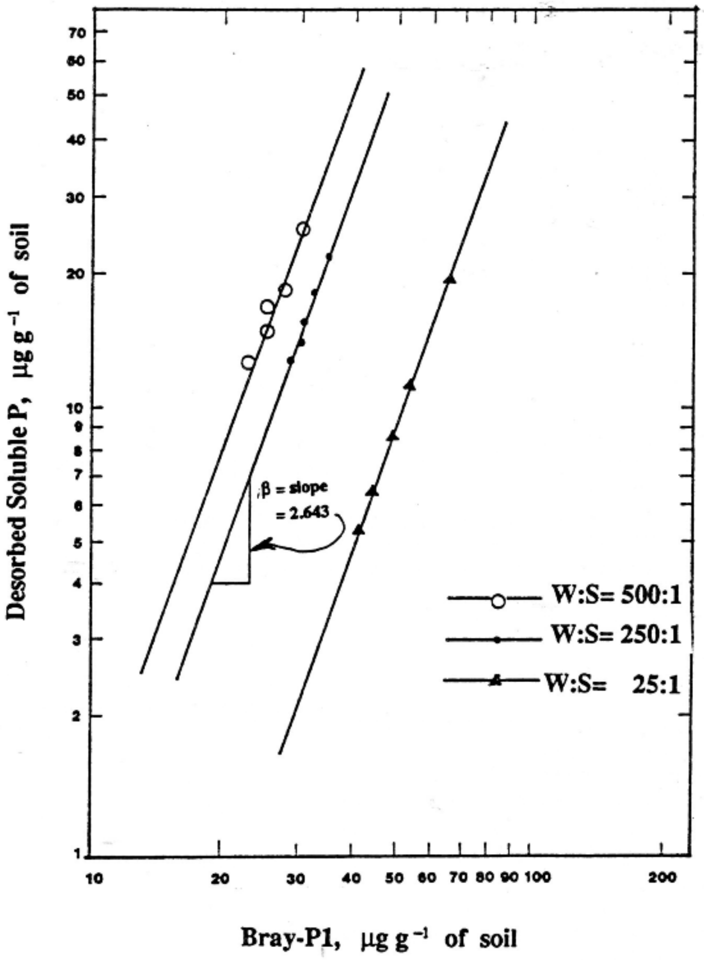

Fig. 3. Desorbed soluble phosphorus from soil samples at different water:soil ratios for Fincastle silt loam at the Stafford watershed.

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  STANDARD PREDATA FILE FOR  BAJGAH ,SHIRAZ IRAN,66/9/21
 RAINFALL DATA FOR 1 RAINGAUGES FOR EVENT OF 11/11/87   PRINT
 GAUGE NUMBER  R1
0    0.   0.00
0    40.   .75
0    60.   3.75
0    80.   0.00
0    100.   .75
0    120.   6.75
0    140.   0.00
0    160.   3.75
0    180.   0.00
0    200.   2.25
0    220.   0.00
1    240.   3.0
 SIMULATION CONSTANS FOLLOW
 METRIC UNITS ARE USED ON INPUT/OUTPUT
 NUMBER OF LINES OF HYDROGRAPH OUTPUT = 101
 TIME INCREMENT = 30. SEC
 INFILTRATION CAPACITY CALCULATED EVERY 180, SECOND
 EXPECTED RUNOFF PEAK = 68.1 mm/HR
  SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW"
 NUMBER OF SOILS =  3
 S 1, TP =.48, FP =.74, FC = 4.50, A = 2.00, P =.65, DF =150.0, ASM =.36, K =.45
 S 2, TP =.38, FP =.45, FC = 8.30, A = 2.00, P =.50, DF = 50.0; ASM =.21, K =.50
 S 3, TP =.38, FP =.45, FC = 8.30, A = 2.00, P =.50, DF = 50.0, ASM =.21, K =.50
 SWITCH=0.0
  SOIL TOTAL PHOSPHORUS AND CONSTANTS OF BRAY P1
 S 1, TOTAL P =485.0, AA1 =0.0000537, BB1 = 1.87500, ALPHA1 = 1.250, BP1 =10.0
 S 2, TOTAL P =585.0, AA1 =0.0000737, BB1 = 2.67500, ALPHA1 = 1.200, BP1 =23.5
 S 3, TOTAL P =385.0, AA1 =0.0000037, BB1 = 2.75000, ALPHA1 = 1.000, BP1 =45.5
   AVERAGE SEDIMENT-BOUND PHOSPHORUS ENRICHMENT RATIO EQUATION:
Ln(PER)=2.48-0.2652Ln(SS)
 DRAINAGE EXPONENT = 3,
 DRAINAGE COEFFICIENT FOR TILE DRAINS = 6.00 mm/24HR
 GROUNDWATER RELEASE FRACTION =   0.0010
  SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOW
 NUMBER OF CROPS AND SURFACES =  2
 C 1, CROP=S.GRAINS, PIT=.04, PER=.40, RC=.45, HU=130., N=.100, C=.15
 C 2, CROP=  FALLOW, PIT=.00, PER=.00, RC=.42, HU=30.0, N=.065, C=.50
  CHANNEL SPECIFICATIONS FOLLOW
 NUMBER OF TYPES OF CHANNELS =  1,
 CHANNEL 1 WIDTH = 0.8  M.,    ROUGHNESS COEFF. = .040
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Fig. 4. An input (predata) file containing phosphorus component parameters.

EXPERIMENTAL WATERSHEDS

Three small agricultural watersheds, the Hoeppner, Ward Road, and Stafford watersheds (Table 1) were simulated using the proposed phosphorus transport model (1). The first two watersheds are located in the Black Creek watershed area northeast of Fort Wayne, Indiana, USA. The third watershed is located near Martinsville, Indiana, southwest of Indianapolis. These three watersheds were chosen because of their differences with respect to soil types, tillage and topography (2).

The amounts of total and Bray-P_1 available phosphorus levels were measured in soil samples for each soil type of the watersheds. Total phosphorus is needed for the sediment-bound phosphorus and Bray-P_1 for the soluble phosphorus transport, respectively. Table 2 gives the data required for the simulation. However, such data can often be obtained from published soil maps or similar sources. Composite soil samples were made to reduce the variability between sample locations. At a given location in a field, five samples were gathered; one at the specific location, and four others, approximately 30 meters in each direction from that location to obtain a composite sample.

Total phosphorus did not change much from location to location within a soil type. In contrast to total phosphorus, Bray-P_1 levels often varied greatly even in one soil type within a watershed. Fig. 5 shows lines of constant Bray-P_1 values for the Hoeppner watershed. A grid was superimposed over this map to find the Bray-P_1 level for each element of each watershed as illustrated in Fig. 5.

Table 1. General description of the experimental watersheds used for simulation.

Watershed	*Area (ha)*	*Crop coverage*	*Area %*	*Soil Type*	*Area %*
Hoeppner	4.26	small grain	41	Blount(BmA)	41
		corn	56	Morley(Mrb2)	42
		pasture	3	(MsC3)	17
Stafford	18.30	corn	100	Fincastle	100
Ward Road	29.0	small grain	50	Houtville(Hs)	45
		corn	50	Nappanee(Na)	55

Table 2. Total soil phosphorus, Bray-P1, and other required data* for the simulation of the watersheds.

Watershed	Soil	Total P	Bray-P1	$Kx10^6$	α	β
Hoeppner:						
	Blount (BmA)	475	12	53.70	1.25	1.875
Morley						
	(MrB2)	497	23	8.70	1.00	2.750
	(MsC3)	506	22	8.70	1.00	2.750
Stafford:						
	Fincastle (FcA)	450	30	18.6	0.833	2.6430
Ward Read:						
	Hoytville (Hs)	705	31	132	1.048	1.9165
	Nappanee (Na)	740	38	223	1,034	1,9340

* For use in the isotherm equation: $P_s = K(WS)^{\alpha} (BP1)^{\beta}$

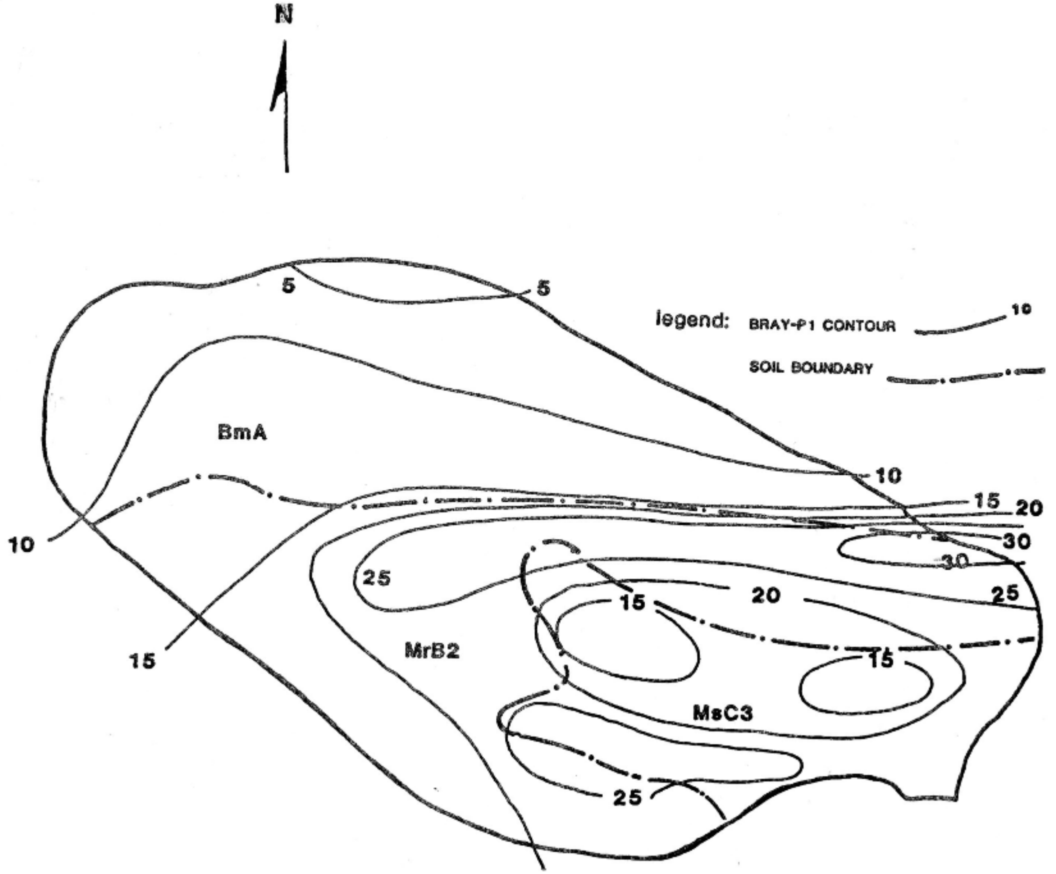

Fig. 5. Constant Bray-P_1 lines for the Hoeppner watershed.

RESULTS AND DISCUSSION

The main purpose of this research was to simulate the loadings of sediment-bound and soluble phosphorus from agricultural watershed. The phosphorus component of the ANSWERS model was obtained using data provided from the Hoeppner and Ward Road watersheds in the Black Creek watershed area. Only the predicted values of Stafford watershed simulation are presented because of lack of observed data at this site.

Hoeppner Watershed Simulation

This experimental watershed has an area of 4.3 ha and a relatively short time of concentration of 28 min due to slope steepness and small size. The watershed has an average slope of 2.7% with a minimum slope of around 0.6% and a maximum slope of around 6.3% .

By superimposing Bray-P_1 "contour" lines on the elemental watershed system, a Bray-P_1 level was assigned to each element. An input data file was then constructed. This file and the superimposed Bray-P_1 levels are shown in Fig. 4 and Fig. 6, respectively. All other information needed in the simulation were as directed by the user's manual for the ANSWERS model (3).

Three storms were simulated: The storm of 9-4-80, the storm of 6-22-81, and the storm of 6-25-81. The storm of 6-25-81 was used to determine the effects of antecedent storm (6-22-81) on phosphorus release.

Fig. 7 shows the actual and simulated hydrographs for storm 9-4-80. Observed and predicted soluble phosphorus losses, and predicted

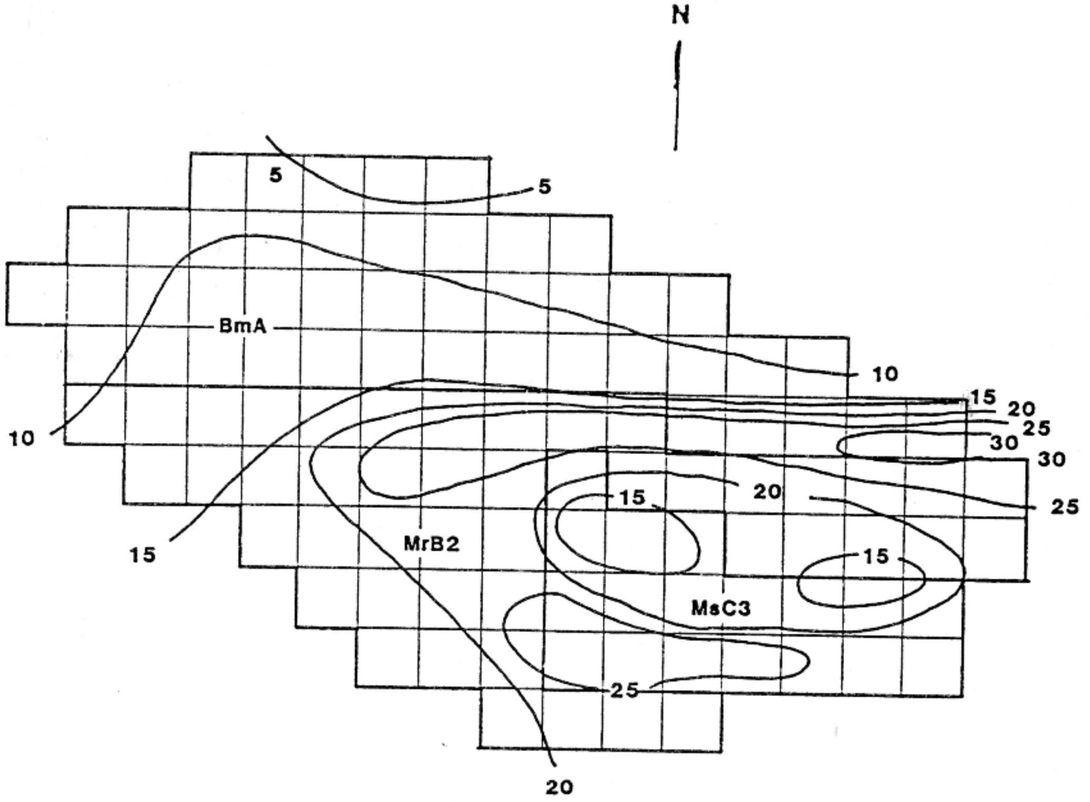

Fig. 6. Constant Bray-P_1 lines superimposed on the grid system of the Hoeppner watershed.

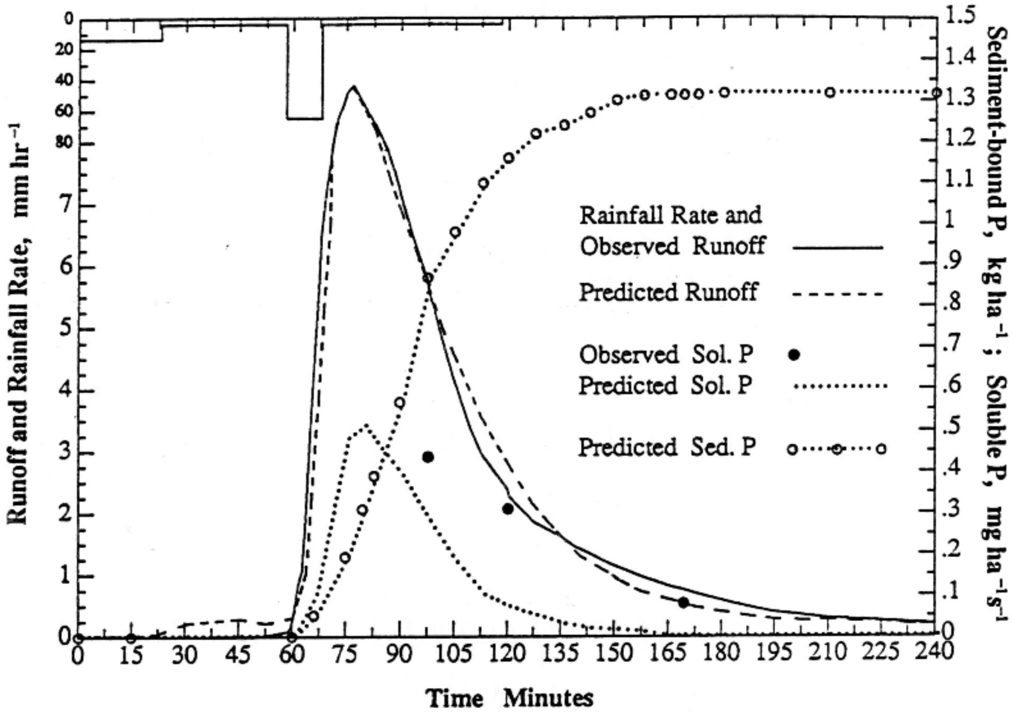

Fig. 7. Hoeppner watershed response, storm: 9-4-80.

sediment-bound phosphorus are also shown. Observed levels of soluble phosphorus were only available for the recession portion of the hydrograph. The predicted soluble phosphorus curve was obtained using the phosphorus component with the ANSWERS model. Generally, as illustrated in Fig.7, a major part of the sediment-bound phosphorus yield occurred during the rising limb of the hydrograph.

As Fig. 7 shows the predicted soluble phosphorus in runoff water from watershed is lower than the observed values. The interaction between available Bray-P_1 phosphorus and soluble phosphorus is governed by equation [2], in which the water:soil ratios (WS) are very important factors. Therefore, the sediment in suspension should be calculated and to be used in the equation of the soluble form of phosphorus released in the runoff water. The prediction of the soluble phosphorus is based on the present erosion component of the ANSWERS model. However, the complexity of the soil erosion from the watershed makes it difficult to predict the sediment load in the suspension with close agreement to the observed values. Therefore, the erosion part of the ANSWERS model should be worked out to find a better watershed and consequently a better estimation of the soluble phsophorus would be gained in turn.

The same procedure used for the storm of 9-4-80 was used to evaluate he storm of 6-22-81. This storm produced a higher amount of runoff and ediment (Fig. 8) from the Hoeppner watershed than the storm of 9-4-80. ig. 8 shows the watershed response to this storm. This Figure also shows asonable agreement between observed and simulated soluble phosphorus, en the limited data which were available. The average concentration of ble phosphorus for this storm was 0.25 mg l^{-1}. However, the first ple was taken 30 min after the peak. Mixing during the high intensity

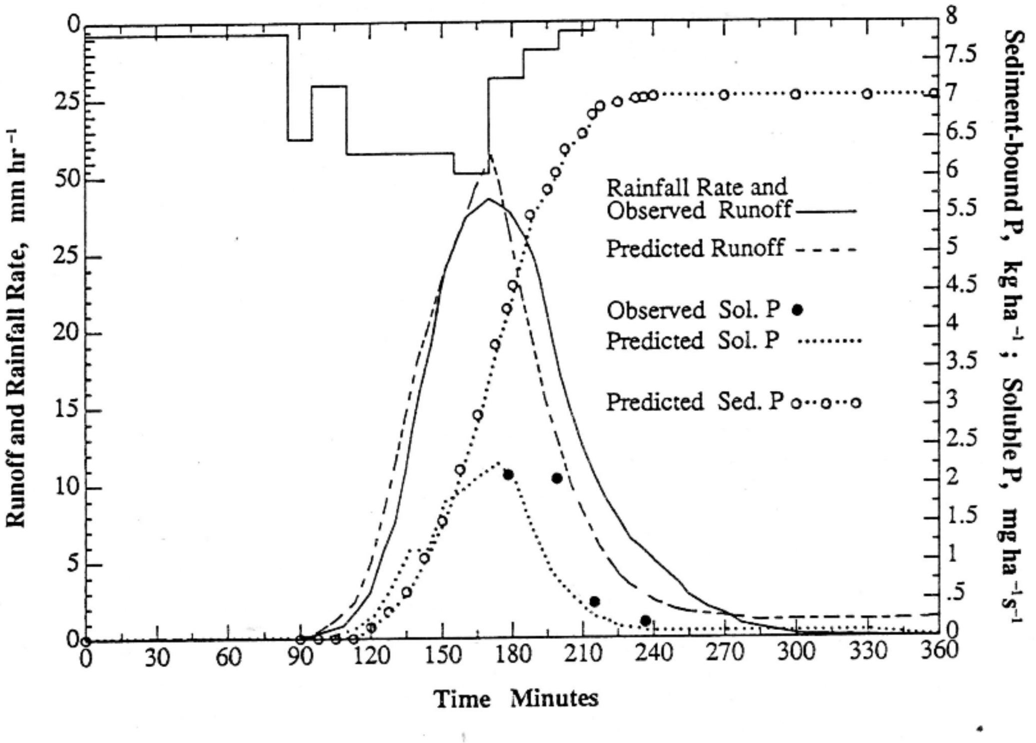

Fig. 8. Hoeppner watershed response, storm: 6-22-81.

period of storm would probably release more phosphorus into runoff water than during the observed period and higher concentrations would be possible. Unfortunately, field samples before the runoff peak were not collected.

Fig. 8 shows a better agreement between observed and predicted soluble phosphorus for storm of 6-22-81. Total sediment-bound phosphorus in this strom is 7 kg ha^{-1} which is about 6 times of the storm of the 9-4-80. High intensity storm and high volume of the runoff caused a higher release of the soluble phosphorus from the soil particles. Therefore, the concentration of the soluble phosphorus is about 5 folds of the previous storm event (storm 9-4-80). When the rainfall ceased or in lower intensity periods of the storm events the concentrations of the soluble phosphorus decreased. This means that the equilibrium between soluble and Bray-P_1 available phosphorus depends on the agitation and mixing caused by the rainfall drops.

The hydrologic response and sediment-bound and soluble phosphorus losses from the Hoeppner watershed for the strom of 6-25-81 are shown in Fig. 9. The observed values of soluble phosphorus were larger than the predicted values. The first sample was taken 70 minutes after the peak and the average soluble phosphorus concentration was only 0.18 mg l^{-1} for this storm. As Fig. 9 shows the rainfall volume and its duration for this storm was less than the storm of 6-22-81. Therefore, the water:soil ratios calculated for prediction of soluble phosphorus are low and consequently the lower concentrations of soluble phosphours were obtained. However, the antecedent rainfall of 6-22-81 may have also reduced the labile phosphours potential by removing the more readily available soil fines or other sources with which equilibrium would be attained. Therefore, the amount of phosphorus released to the runoff was smaller and a lower concentration was detected than that which likely occurred for the previous storm because of the time it takes for the labile phosphorus to come into equilibrium with particulate phosphorus.

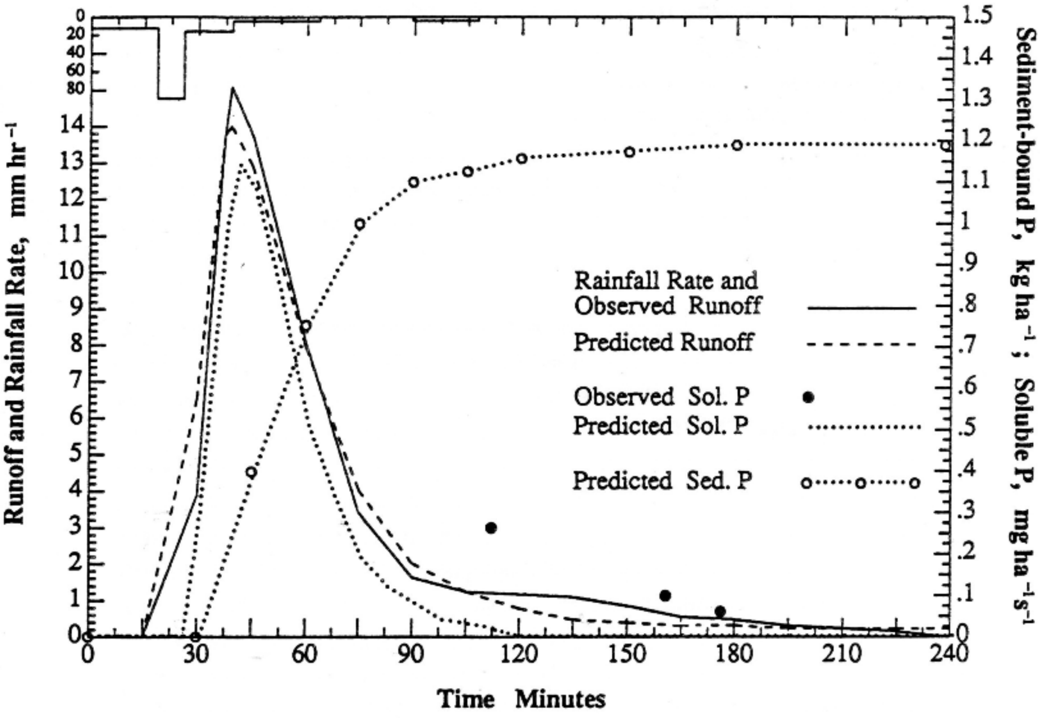

Fig. 9. Hoeppner watershed response, storm: 6-25-81.

Ward Road Watershed

This small watershed has a drainage area of 29 ha and is located in the south part of the Black Creek watershed (2). It is quite flat, having an average slope of 0.38 percent and a time of concentration of 75 min. Although the two soil types are scattered throughout this watershed, the upper part is primarily Hoytville silty clay (fine, illitic mesic, Mollic Ochraqualfs), Hs, and the lower part primarily Nappanee silt loam (fine, illitic, mesic Aeric Ochraqualfs), Na. These two soils were found on the glacial Lake Maummee plain. In general, these soils have a mild slope and are poorly drained. In 1981, this site had corn in the upper portion and small grain in the lower portion (Table 1).The required data for simulation of this site are presented in Table 2.

The storm of 6-22-81 which was recorded in a weather station, less than half of a kilometer from the watershed, was used. Fig. 10 shows the responses of this watershed to the storm of 6-22-81. The hydrographs are in fairly close agreement. Fig. 10 shows the observed and predicted soluble phosphorus levels for the storm. Accumulated sediment-bound phosphorus losses are also shown. However, lack of good sediment data makes it impossible to compare the simulated and observed sediment-bound phosphorus yields.

Stafford Watershed Simulation

This 18.4 ha watershed is located near Martinsville, southwest of Indianapolis, Indiana, USA. It has an average slope of 1.5% , ranging from 0.2 to 4.5% , and a time of concentration of 64 min. Only one soil type, FcA, is located on this watershed. To show the capability of new component of the ANSWERS model, it is assumed that all three watersheds were planted by corn. The storm of 6-22-81 at Hoeppner watershed was then used for all simulation so that loadings could be compared.

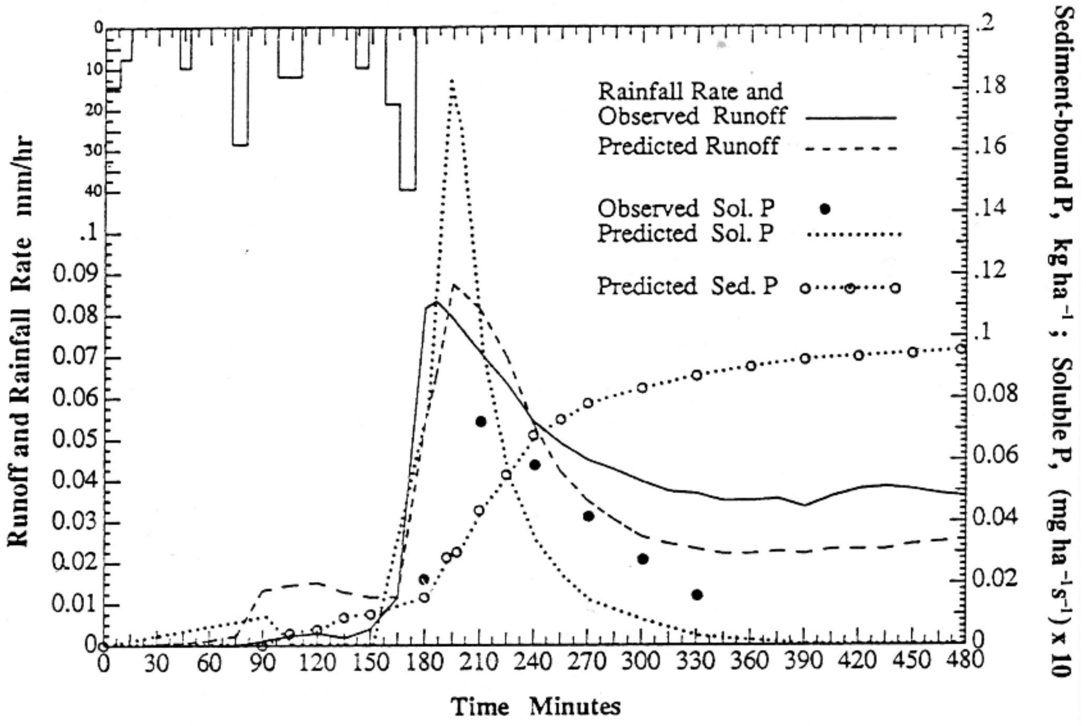

Fig. 10. Ward Road watershed response, storm: 6-22-81.

Fig. 11 shows the simulated sediment-bound phosphorus yields from the three watersheds. The total phosphorus concentration of the soils of the Ward Road watershed is around 725 μg g^{-1} soil almost twice as high as total phosphorus of around 450 μg g^{-1} soil of the other two sites (Table 2). This results in a relatively large increase in sediment-bound phosphorus for the Ward Road watershed.

The total soluble phosphorus loadings from these three watersheds are also shown in Fig. 11. Total yields from the three sites are fairly close together. The Hoeppner watershed had the highest total runoff and sediment yield. However, the average Bray-P_1 level at the Stafford watershed was almost twice that of Hoeppner watershed (30 μg g^{-1}soil). The Ward Road watershed had the least sediment loss and the lowest total runoff of any of the watersheds but the Bray-P_1 level of its soils was very high especially near the outlet where a high proportion of erosion occurred. Here the soil sampling showed Bray-P_1 levels of 40 to 100 μg g^{-1} soil. Consequently, the loading of soluble phosphorus from Ward Road watershed is relatively high.

SUMMARY AND CONCLUSIONS

A phosphorus transport component has been developed for the ANSWERS model to simulate the loading of sediment-bound and soluble phosphorus from agricultural watersheds during single storm events. The transport process is limited to overland flow because the ANSWERS model does not account for channel erosion.

Since the ANSWERS model is a distributed parameter model, information is needed to describe elemental areas which are considered uniform. For each element, in addition to soil hydrological properties and land use practices, data about the soil phosphorus condition (including in our case total phosphorus and Bray-P_1 available phosphorus) must be specified before simulating a watershed. This information can be obtained through soil survey maps, topographic maps, and soil sampling.

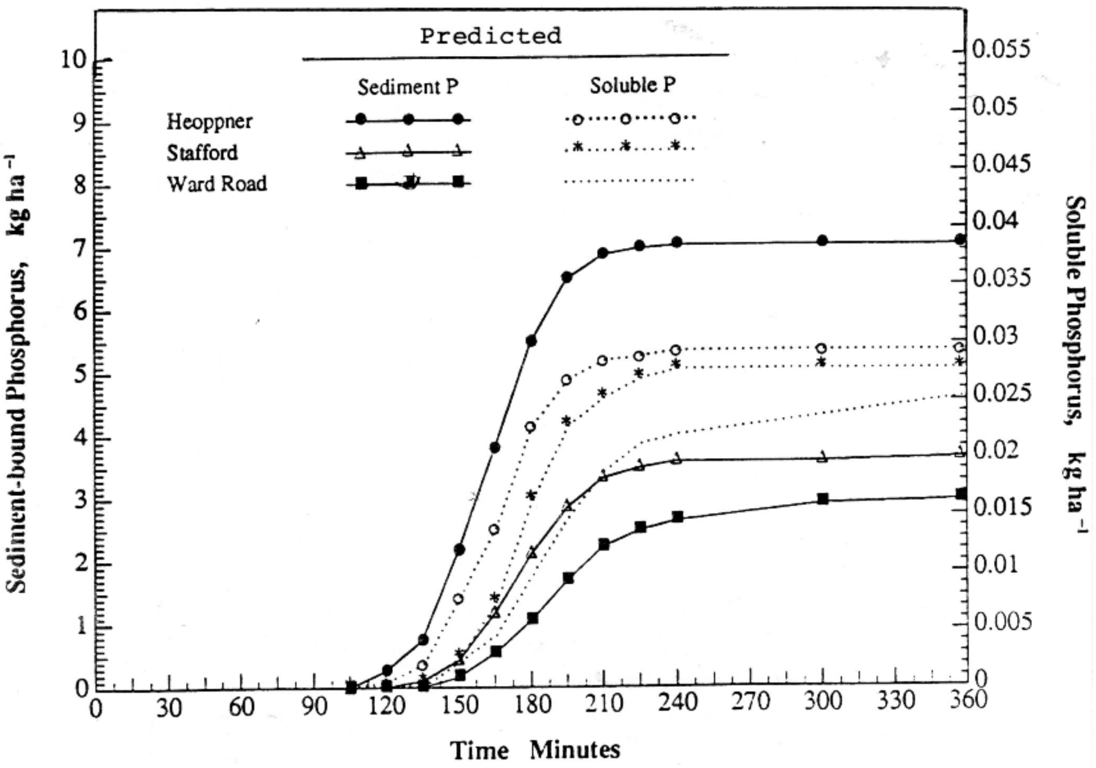

Fig. 11. Predicted sediment-bound and soluble phosphorus yields from the Hoeppner, Stafford, and Ward Road watersheds using the storm of 6-22-81 at the Hoeppner watershed .

The model was applied to two small agricultural watersheds in the Black Creek watershed area to check the validity of the phosphorus component in comparison with observed field data. Rather fair agreement with observed values was obtained from somewhat limited data. The phosphorus transport model was then used to simulate the two watersheds and another one located outside the Black Creek watershed area, all under similar rainfall and cropping conditions. The results of these simulations were compared to gain a clearer understanding of the influence of basic cultural conditions affecting runoff, soil loss and phosphorus yields. The phosphorus yields, especially the soluble form, was relatively high for the flattest watershed, from which soil loss was low. This was due to the high Bray-P_1 levels near the outlet, suggesting that some degree of phosphorus fertilizer reduction is in order.

Some Specific Conclusions Of This Research Are:

1. The phosphorus transport component to the ANSWERS model has the ability to simulate a different soil and topographic conditions.

2. Simulation of two small agricultural watersheds showed that the phosphorus component gives rather fair agreement between simulated results and observed field data. There is some evidence that antecedent storms have a reducing effect on subsequent phosphorus yields. Some accounting of the labile phosphorus processes occurring between storms may be needed to give more accurate simulations.

3. Remedial actions can be planned for cost-effective of the impact of phosphorus yields on receiving bodies of water by comparing dissimilar watersheds under similar cropping and storm conditions. In our case, a cost-effective method of reducing phosphorus yields from the relatively steep Hoeppner watershed might be accomplished using soil conservation practices to control erosion. On the other hand, a cost-effective method of

reducing phosphorus yields from the relatively flat Ward Road watershed may be through better fertilizer management in which the Bray-P_1 available phosphorus level would be maintained more in line with crop needs.

4. Sediment-bound and soluble phosphorus yields are highly dependent on the enrichment ratio and isotherm curves, respectively. Good definition of the equations for these curves is necessary for increased accuracy of phosphorus yield predictions.

5. In the equilibrium equation of the soluble phosphorus and Bray-P_1 available phosphorus the instantaneous equilibrium was assumed. This assumption is true of the high intensity rainfalls because high energy of mixing associated with the fall velocity of the rainfall droplets. However, the equilibrium between these forms of phosphorus is time dependent. It seems that for simulation of the lower rainfall intensities a time factor coefficient should be used in equation [2] for better estimation of the soluble phosphorus. This needs further research in the future.

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