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PHOSPHATE CONTENT OF GREAT BASIN GROUND WATERS AND METHODS FOR APPRAISING THEIR CONTAMINATION POTENTIAL

by

Frederick Charles Shewman

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

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in

Civil Engineering

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Frederick C Shewman

Frederick C. Shewman

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ABSTRACT

Phosphate Content of Great Basin Ground Waters
and Methods for Appraising Their Contamination Potential

by

Frederick Charles Shewman, Doctor of Philosophy

Utah State University, 1971

Major Professor: Dr. Howard B. Peterson
Department: Civil Engineering

The current phosphate status of Great Basin ground waters of Utah was investigated. A theoretically expected phosphate concentration was determined. Soils were selected and their phosphorus disposal capacities were determined by column and repeat treatment testing methods. A program was developed for computing a soil's maximum phosphorus disposal capacity by utilizing data from the repeat treatment test.

Published and unpublished data were gathered on the dissolved orthophosphate content of the ground waters of the Great Basin area of Utah and a cooperative well sampling and analysis program was carried out. Analyses of 183 ground water samples showed a range in orthophosphate content of from 0.00 to 0.93 mg/l as P, with a mean concentration of 0.027 mg/l as P.

These data were used along with solubility theory calculations to establish an approximate level of orthophosphate concentrations which might be expected to exist in average ground waters of the Great Basin area of Utah. It appeared that the closest approximation

to natural orthophosphate concentrations in these ground waters could be made by assuming a solubility equilibrium existed with the calcium phosphate hydroxyapatite. Combining this information with the most severe conditions found with respect to ionic strength and calcium concentration in the ground water, any concentration above about 0.2 mg/l as P would probably indicate that either sample contamination or actual pollution of the ground water had occurred. This information and approach should prove useful in the future for detecting pollution or establishing quality standards in a given geologic area.

Five soils were selected as representatives of some of the various potentially irrigable types in the Great Basin. These were studied in order to develop the best testing procedures to indicate both the maximum phosphorus disposal capacity of the soils in an area to be used for land disposal of phosphorus laden waters, and the maximum ground water pollution hazard that existed in such an area if no special care was taken in applying the effluent. The Langmuir adsorption isotherm approach for determining a soil's phosphorus disposal capacity was discussed and data was presented which apparently eliminated it for this purpose.

A repeat treatment test was developed which was shown to be superior to the adsorption isotherm approach for determining the maximum phosphorus disposal capacity of a soil. Data from this test were used in conjunction with a computer-solved soil model

to obtain numerical values of the maximum phosphorus disposal capacity of any given soil profile.

Soil column tests were made and compared to the repeat treatment data. The data from the two types of tests indicated the possible large differences in phosphorus disposal capacity which might be encountered depending upon the concentration of phosphorus and how the phosphorus laden water was applied. The phosphorus disposal capacity values obtained from the column tests were found to be estimates of the least amount of phosphorus that would be removed from an effluent by a soil.

It was concluded from a consideration of all the data that the maximum phosphorus disposal capacity of a soil would result from a combination of adsorption of phosphate and precipitation of compounds of phosphorus. The soil properties in Great Basin soils most likely correlated with adsorption would be surface area and the related properties, percent clay and cation exchange capacity. The amount and condition of lime present probably influences both adsorption and precipitation. It was evident that the phosphorus concentration of the water and the method of application greatly affect the amount of phosphorus fixation by any given soil.

(174 pages)

INTRODUCTION

One current problem in the field of water quality management is that of nutrient pollution. Nitrates and phosphates remaining in effluents after secondary waste treatment are often responsible for accelerating the natural process of eutrophication in lakes and streams. This acceleration is considered by most conservationists to be quite detrimental. In different situations, depending on the natural quality of the water derived from its watershed, one or both of these nutrients may be growth-limiting. However, phosphorus is often singled out since some types of algae, notably the blue-greens, are able to "fix" their own nitrogen.

Some form of tertiary treatment is needed to reduce the level of growth-stimulating phosphorus in a waste effluent. With the current emphasis on conserving water, and knowing that it will have to be renovated for reuse, one type of tertiary treatment that has practical possibilities is to apply the effluent to the land. This is attractive since water not consumed by a crop may recharge depleted groundwater supplies. The water thus stored is protected from evaporation losses, and from the standpoint of aesthetics this is probably the most acceptable method of treatment and storage.

Before effluents are discharged an assessment should be made of the possibilities of polluting the groundwater. Groundwaters containing

high concentrations of phosphorus might be a continuing source of nutrient to a surface water body. In such cases an effort should be made to prevent such contamination of the natural ground water quality.

This study was undertaken to determine the feasibility of future renovation of waters containing phosphorus by land application in the Great Basin area of Utah. The objectives were (1) To determine the phosphorus content of the groundwaters of the Great Basin (Utah). This would serve as a basis for setting standards and for detecting present and future pollution. (2) To determine the phosphorus fixing capacity of some major Great Basin soils as a basis for treatment design. (3) To develop a procedure for determining the potential "phosphorus disposal capacity" of soils to be used for effluent treatment.

REVIEW OF LITERATURE

Phosphorus Fixation by Soils

General considerations

Hemwall (1957, p. 101) defines fixation as "the process whereby readily soluble compounds are changed into less soluble forms by reaction with inorganic or organic components of the soil with the result that the compounds become restricted in their mobility in the soil." This definition, although seemingly simple, is so completely qualitative that it is hard to realize how much research has been done on the fixation of phosphorus by soils. Reports of this phenomenon in the literature date back to 1850 (Wild, 1950). Extensive and detailed studies have been undertaken to ascertain the various mechanisms of fixation as a means for determining how much of a given amount of applied phosphorus remains in the soil solution. Most of the interest and research has been applied to the fertility aspects of fixation.

In agriculture, a soil having a high capacity to fix phosphorus presents a problem by making it unavailable to plants, but for treatment of waste effluent such a soil is most desirable. The greater the soil's fixing capacity, the more efficient and longer lasting its treatment effects will be.

In any future feasibility study involving renovation by the soil of phosphorus-laden waters, two questions are certain to arise. One is

the possible pollution of ground waters, and the other is the soils' capacities to continue to remove phosphorus.

In studying phosphorus fixation capacities of soils, various factors may play an important role. Bailey (1968) lists type of soil, particle size, pH, reduction potential, temperature, organic content, and reaction time. Sauchelli (1965) lists concentration of added phosphorus, reaction time, temperature, pH, and nature of the adsorbing material. Perkins, Dragsdorf, and Bhangoo (1957) list reaction time, pH, amount of phosphate added, and amount of soluble sesquioxides Phosphate concentration, reaction time, temperature, pH, type of minerals in the soil, particle size, exchangeable cations, and salt effects are all listed in the review edited by Pierre and Norman (1953).

As to the effects of the various factors influencing phosphorus retention by soils there is much disagreement. On the question of the effect of organic matter, for example, Saini and MacLean (1965) concluded from a study of 24 New Brunswick soils that organic matter is directly related to phosphorus retention capacity. Harter (1969), in a study of eight Connecticut soils, found that, of five soil properties examined, percent organic matter was the most positively correlated to phosphorus adsorption. Rennie and McKercher (1959) also found the organic fraction to have a high phosphorus adsorption capacity in four Saskatchewan soils. However, Bailey (1968), in his review, stated that organic matter may either retard or enhance fixation. Bear (1964, p. 382) stated, "In general, the overall effect of the organic phase in soils has

been found to be such as to decrease phosphorus fixation." Sauchelli (1965) listed a good supply of readily decomposable organic matter as one factor favoring phosphorus solubility in a soil. Dalton, Russel, and Sieling (1952), Doughty (1935), Struthers and Sieling (1950), Heck (1934), Fox and Kamprath (1970), and Larsen, Langston, and Warren (1958), all found phosphorus retention inversely related to the amount of organic matter present.

As would be expected, increased reaction time generally has been found (Sen Gupta and Cornfield, 1963; Benko, Hampl, and Vnuk, 1963; Perkins, Dragsdorf, and Bhangoo, 1957; Lindsay, Peech, and Clark, 1959) to increase phosphorus fixation. Increasing the concentration of the phosphorus solution in contact with the soil also increases fixation (Sauchelli, 1965; Benko, Hampl, and Vnuk, 1963; Haseman, Brown, and Whitt, 1950).

Mack (1959) found that by increasing the temperature, an increased amount of water soluble phosphorus could be leached from a soil system. Clark and Turner (1955), however, found increased fixation at higher temperatures, as did Haseman, Brown, and Whitt (1950).

Any statement regarding what position in the soil profile has the greatest capacity to fix phosphorus apparently cannot be general in nature. Bailey (1969, p. 41) stated "the greatest phosphorus fixation capacity appears to be in the A horizon," but Ellis and Erickson (1969), in studying Michigan soils, found the highest phosphorus adsorption

maximum in the A horizons of nine soils, the B horizons of fifteen soils, and the C horizons of four soils.

The pH or soil reaction affects fixation in different ways but generally fixation is least in nearly neutral soils, with pH from 6.5 to 7.5 (Cho and Caldwell, 1959; Bailey, 1968; Sauchelli, 1965). Sauchelli (1965) and Olsen and Watanabe (1957) credit acid soils as having the highest fixation capacity. In acid soils there is generally more iron and aluminum available in solution to combine with soluble phosphate and precipitate it from the soil solution. The compounds are generally of the form $M(H_2O)_3\ (OH)_2H_2PO_4$ (Hemwall, 1957). Most writers have pointed to aluminum or iron or both as dominating phosphorus fixation in acid soils (Bailey, 1968; Bear, 1964; Bass and Sieling, 1950; Cho and Caldwell, 1959; Cole and Jackson, 1951; Coleman, Thorup, and Jackson, 1960; Hall, 1966; Haseman, Brown, and Whitt, 1950; Heck, 1934; Hemwall, 1957; Hsu, 1964, Larsen, Langston, and Warren, 1958; Perkins, Dragsdorf, and Bhangoo, 1957; Ramulu, Pratt, and Page, 1967, Saini and Maclean, 1965; Wild, 1953, Wright and Peech, 1960).

In alkaline soils fixation would be expected to occur mostly as calcium phosphates (Bailey, 1968; Cho and Caldwell, 1959; Olsen, Watanabe, and Cole, 1960a; Hemwall, 1957). The controlling factors in this case are mainly pH and Ca^{++} concentration. The pH controls which phosphate ion is dominant, and the solubility of $CaCO_3$. Thus the pH determines the $[Ca^{++}]$, which controls calcium phosphate solubility by the common ion effect (Bear, 1964; Cole and Olsen, 1959).

Soils having a very high pH (8.5 and above) are likely to contain large amounts of alkali carbonates which precipitate all the Ca^{++} as $CaCO_3$ by the $CO_3^{=}$ common ion effect. With reduced $[Ca^{++}]$ there is less fixation of phosphorus (Bear, 1964; Sauchelli, 1965).

Salts in solution have various effects on phosphorus solubility in soils, possibly increasing or decreasing it depending on the situation. According to the law of Debye-Huckel, $-\log \gamma = 0.509 Z^2 \sqrt{I}$, any ionized salt in solution increases the solubility of other salts to some extent by increasing the ionic strength, I, thereby decreasing the activity coefficient, γ. This decreases the activity, or "effective concentration" of the salt, thereby increasing its solubility. Another possible salt effect is that certain ions can replace or release adsorbed phosphate ions. Arsenate, silicate, citrate, bicarbonate, borate, oxalate, hydroxyl, and fluoride ions are capable of this (Bear, 1964; Sauchelli, 1965). The common ion effect plays an important role either by increasing fixation (precipitation) of phosphates with a common ion (Buehrer, 1932; Kittrick, and Jackson, 1955; Wild, 1950) or decreasing fixation by precipitating out a salt that has a common ion to a phosphate salt (Bear, 1964). Some investigators (Clark and Peech, 1960 and Lehr and Van Wesemael, 1952) have found that even neutral salts increase phosphorus fixation.

In such a general discussion the vital importance of the clay fraction of soils in fixation, although implicit in much of the foregoing material, should be formally pointed out. Sauchelli (1965) states it most

strongly by saying fixation takes place only in the clay size fraction of soils. Olsen and Watanabe (1957) found phosphorus sorption was directly related to surface area and Sen Gupta and Cornfield (1963) found fixation more correlated with clay content than with percent lime in calcareous soils. Apparently further illustrating the importance of clay, Neller (1946), Spencer (1957), Krone, McGauhey, and Gotaas (1957), and Fox and Kamprath (1970) found a lack of phosphorus retention in very sandy soils.

Some of the above-mentioned information on fixation can be summarized by examples. As Bear (1964) points out, considering gibbsite $Al(OH)_3$, $K_{sp} = [Al^{3+}][OH^-]^3$, and goethite $Fe(OH)_3$, $K_{sp} = [Fe^{3+}][OH^-]^3$ as the main sources of Al^{3+} and Fe^{3+} for reaction with phosphates in some soils, it is clear from the solubility products that a rise in pH (increase in $[OH^-]$) will greatly reduce the availability of Al^{3+} and Fe^{3+} and hence reduce precipitation of iron and aluminum phosphates. A similar situation exists if the aluminosilicate, kaolinite, $K_{sp} = [Al^{3+}][OH^-]^2[HSiO_3^-]$, is considered as a typical example of the Al^{3+} source.

Considering the implications of the above discussion, some pollution potential areas can be in very sandy soils, some highly organic soils, or in alkali soils. Increasing the pH of an acid soil laden with phosphorus (see Figure 1) could create a pollution hazard by a release of phosphorus. Also interactions with ions of various salts, such as fluoride, citrate, oxalate, etc., might cause phosphates to be released into the ground water.

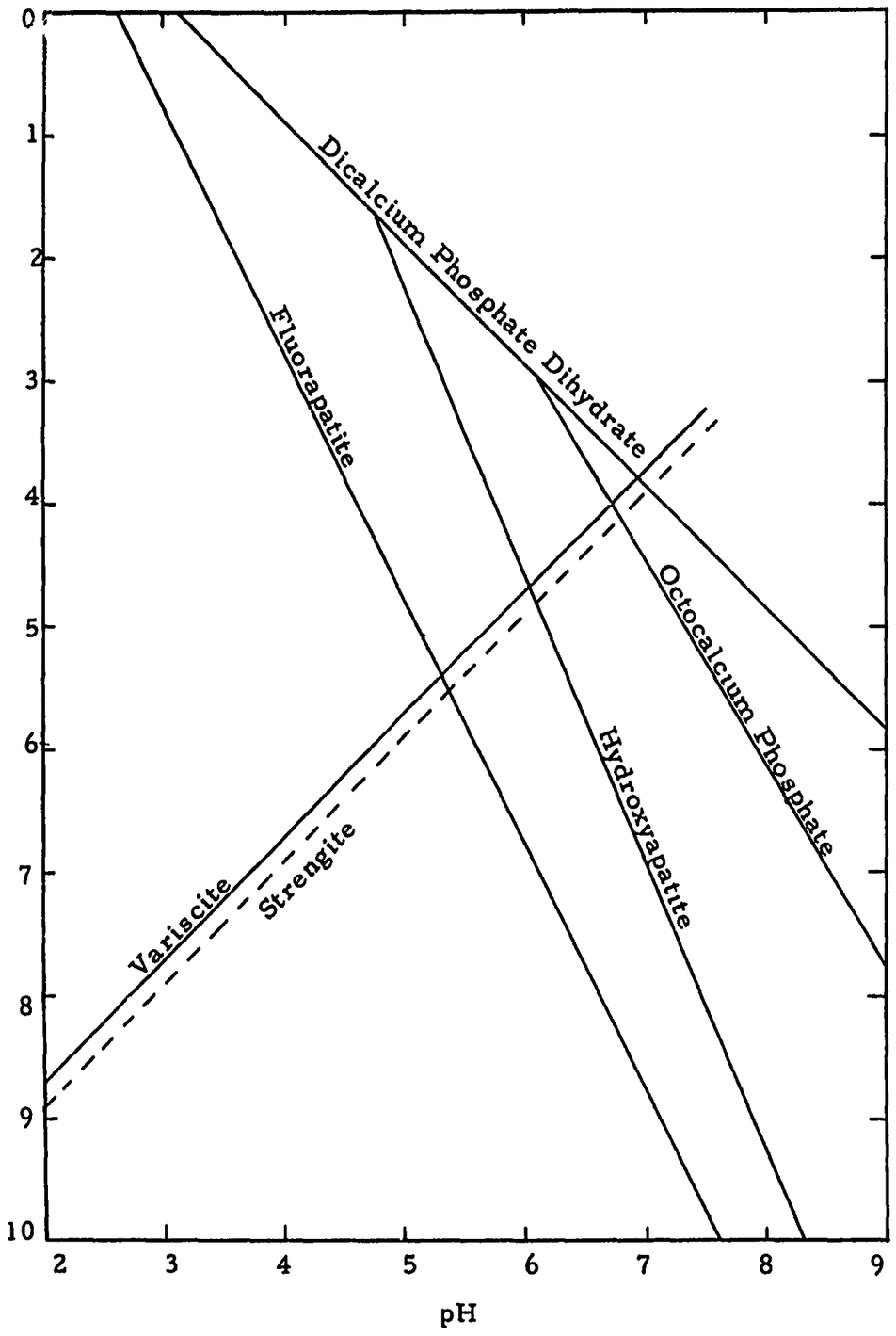


Figure 1. Solubility Diagram for Phosphate Compounds in Soils at 25°C and 0.005 M Ca Concentrations. (after Lindsay and Moreno, 1960).

Solubility theory

Much work has been done with solubility theory which lends itself to possible application in calculating theoretical phosphate equilibrium values which may occur in the soil solution. Writers such as Lindsay and Moreno (1960) point out the probability that most of the more insoluble phosphate compounds reach equilibrium with solution very slowly and only the most soluble compounds dissolve and precipitate fast enough to affect the phosphate activity in soils. Hence solubility measurements in soils often will not correspond to any known solubility product. However, the theory is still of interest in defining boundary limits of solubility set by the thermodynamically stable compounds.

In calcareous soils, the apatites--hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, and fluorapatite, $Ca_{10}(PO_4)_6F_2$, are generally considered to be the stable end products of fixation when phosphate is added to the soil (Clark, 1955; Clark and Turner, 1955; Hsu and Jackson, 1960; Murrmann and Peech, 1969). In acid soils, some crystalline mineral of the variscite, $Al(OH_2)H_2PO_4$ --strengite, $Fe(OH)_2H_2PO_4$ isomorphous series is usually the end product (Wright and Peech, 1960; Lindsay, Peech and Clark, 1959; Hsu and Jackson, 1960; Hemwall, 1957; Chang and Jackson, 1957).

In calcareous soils, the compound dicalcium phosphate dihydrate, $CaHPO_4 \cdot 2H_2O$, has been found (Clark and Turner, 1955; Moreno, Brown, and Osborn, 1960a; Moreno and Osborn, 1963; Olsen, Watanabe,

and Cole, 1960b) to be one of the first detectable intermediate compounds on the way to fixation as a stable apatite. Hence, in a potential wastewater application problem it may be more realistic to consider phosphate activity in the soil solution as being governed by dicalcium phosphate dihydrate than by the apatites. Weir and Soper (1962) and Withee and Ellis (1965) state that phosphate activity in calcareous soils is governed by dicalcium and octocalcium phosphates which dissolve or precipitate fast enough to affect the phosphorus concentration in solutions.

Lindsay and Moreno (1960) have developed a solubility diagram (Figure 1) which could be used to predict equilibrium phosphate concentrations in a soil solution upon addition of enough phosphorus-laden water to permit the formation of any of the phosphate compounds given. They have also compiled a table of information (Table 1) which is invariably of interest when dealing with phosphate equilibrium calculations.

The solubility diagram in Figure 1 is based on the assumption that iron, aluminum and fluorine activities in soils are governed by the solubilities of goethite, gibbsite, and fluorite, respectively, and calcium concentration is set arbitrarily at 0.005 molar. As more specific information becomes available about these activities, the diagram can be modified accordingly. The equations for the lines on the diagram are given (Lindsay and Moreno, 1960) as follows:

for strengite, $pH_2PO_4 = pK_{st} - pK_{gt} + pK_w - pH$

for variscite, $pH_2PO_4 = pK_v - pK_g + pK_w - pH$

Table 1. Solubility Products and Dissociation Constants at 25° C Used in the Development of Figure 1. (after Lindsay and Moreno, 1960).

Compound or species	Chemical formula	Solubility expression when activity of $H_2O = 1$	Value of pK
Gibbsite	$Al(OH)_3$	$pK_g = pAl + 3pOH$	33.8
Variscite	$Al(OH)_2PO_4$*	$pK_v = pAl + 2pOH + pH_2PO_4$	30.5
Goethite	FeOOH	$pK_{gt} = pFe + 3pOH$	Unknown
Ferric hydroxide	FeOOH	$pK_{fh} = pFe + 3pOH$	38.1
Strengite	$Fe(OH)_2H_2PO_4$*	$pK_{st} = pFe + 2pOH + pH_2PO_4$	33.6-35.0
Dicalcium phosphate dihydrate	$CaHPO_4 \cdot 2H_2O$	$pK_{dcpd} = pCa + pHPO_4$	6.56
Dicalcium phosphate anhydrous	$CaHPO_4$	$pK_{dcpa} = pCa + pHPO_4$	6.66
Octocalcium phosphate	$Ca_4H(PO_4)_3 \cdot 3H_2O$	$pK_{ocp} = 4pCa + pH + 3pPO_4$	46.91
Hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$	$pK_{ha} = 10pCa + 6pPO_4 + 2pOH$	113.7
Fluorapatite	$Ca_{10}(PO_4)_6F_2$	$pK_{fa} = 10pCa + 6pPO_4 + 2pF$	118.4
Fluorite	CaF_2	$pK_{ft} = pCa + 2pF$	9.84
Calcite	$CaCO_3$	$pK_{cc} = pH - 1/2\ pCa + 1/2 \log P_{CO_2}$	4.93
Phosphoric acid	H_3PO_4	$pK_1 = pH + pH_2PO_4 - pH_3PO_4$	2.12
Dihydrogen phosphate ion	$H_2PO_4^-$	$pK_2 = pH + pHPO_4 - pH_2PO_4$	7.20
Monohydrogen phosphate ion	$HPO_4^=$	$pK_3 = pH + pPO_4 - pHPO_4$	12.32
Water	H_2O	$pK_w = pH + pOH$	14.00

*The chemical formulae for variscite and strengite may also be expressed as $AlPO_4 \cdot 2H_2O$ and $FePO_4 \cdot 2H_2O$, respectively.

for dicalcium phosphate dihydrate, $pH_2PO_4 = pK_{dcpd} - pK_2 - pCa + pH$

for octocalcium phosphate, $pH_2PO_4 = 1/3\ pK_{ocp} - pK_2 - pK_3 - 4/3\ pCa + 5/3\ pH$

for hydroxyapatite, $pH_2PO_4 = 1/6\ pK_{ha} - pK_2 - pK_3 - 1/3\ pK_w - 5/3\ pCa + 7/3\ pH$

for fluorapatite, $pH_2PO_4 = 1/6\ pK_{fa} - 1/6\ pK_{ft} - pK_2 - pK_3 - 3/2\ pCa + 2\ pH$

As an example of how this information might be used in a practical situation, the following is considered:

Assume sewage effluent, 10 mg/l in P, is to be applied over an area of calcareous soils. Preliminary tests on the effluent and soil solution indicate that the new overall soil solution will consist essentially of $CaCl_2$ at about 0.01 M, and NaCl at about 0.005 M, with a pH of about 7.8. How much P will be removed?

Assuming that percolation time of the effluent will be short enough such that an equilibrium with dicalcium phosphate dihydrate will be formed, the appropriate equation is,

$$pH_2PO_4 = pK_{dcpd} - pK_2 - pCa + pH$$

Using data from Table 1,

$$pH_2PO_4 = 6.56 - 7.20 - pCa + 7.80$$

$$pH_2PO_4 = 7.16 - pCa$$

To find activity of Ca^{++}, the activity coefficient γ_{Ca} must be calculated. Using the limiting law of Debye-Hückel,

$$-\log\gamma = 0.51\ Z^2\sqrt{I}$$

where

Z = valence of ion

I = ionic strength of solution

and, $I = 1/2\ \Sigma\ c_i\ Z_i^2$

where

c_i = concentration of ion

To find I for this soil solution:

	c_i	Z_i	$c_i Z_i^2$
Ca^{++}	.01	2	.040
Na^+	.005	1	.005
Cl^-	.025	-1	.025
		Σ	.070

$$I = 1/2\ \Sigma c_i\ Z_i^2 = 0.070/2 = 0.035$$

Hence for γ_{Ca},

$$-\log\gamma = 0.51\ (4)\sqrt{.035}$$

$$\gamma_{Ca} = 0.415$$

So, $a_{Ca} = \gamma_{Ca} C_{Ca} = .415\ (.01) = 4.15 \times 10^{-3}$ M

Then, $pCa = -\log a_{Ca} = 2.38$

So, $pH_2PO_4 = 7.16 - 2.38 = 4.78$

and $a_{H_2PO_4} = 1.66 \times 10^{-5}$ M

To convert $a_{H_2PO_4}$ to total P, the following equation is used (Ellis and Erickson, 1969) which arises from the three ionization equations for phosphoric acid (Table 1).

$$\text{Total P} = \frac{a_{H_2PO_4}}{\gamma_{H_2PO_4}} + \frac{a_{H_2PO_4} \times 10^{-7.2}}{[H^+]\ \gamma_{HPO_4}}$$

$\gamma_{H_2PO_4}$ and γ_{HPO_4} are found from Debye - Hückel to be 0.802 and 0.415, respectively. $[H^+] = 10^{-7.8}$ was given.

Hence,

$$\text{Total P} = \frac{1.66 \times 10^{-5}}{.802} + \frac{1.66 \times 10^{-5} \times 10^{.6}}{.415}$$

Total P = 1.8×10^{-4} M or 5.64 mg/l P left in the soil solution.

Therefore only 43.6% of the P is removed by precipitation as dicalcium phosphate dihydrate. If equilibrium with octocalcium phosphate had been reached, 0.39 mg/l P would have been left in the soil solution.

Had the retention time of the effluent been long enough such that an equilibrium with hydroxyapatite could have been reached, only 3.38 x 10^{-4} mg/l P would have remained in the soil solution. However, equilibrium is reached so slowly with the more insoluble calcium phosphate compounds that precipitation alone probably removes something nearer to the two former amounts.

Leckie and Stumm (1970), in studies of phosphate precipitation, also found the formation of apatites to be very slow, but observed the precipitation of phosphates with iron and aluminum to be rapid. Therefore, the variscite and strengite equations given in Table 1 are probably realistic to use in solubility calculations involving soils high in iron or aluminum.

Isotherm theory

Another possibility for theoretical calculation of the amount of phosphate fixed by a given soil is by the use of the Langmuir adsorption equation. It was developed from the kinetic theory of gases by I. Langmuir in 1918 for adsorption of gases on solids, but since that time many investigators (Cole, Olsen, and Scott, 1953; Olsen and Watanabe, 1957; Rennie and McKercher, 1959; Edwards, 1968; Ellis and Erickson, 1969) have shown that data from the removal of phosphorus by a soil from liquid solution fits the equation reasonably well. The range of conformance to the isotherm is restricted to somewhat low equilibrium phosphorus concentrations, with most authors reporting deviations when final

P concentrations were above about 15 mg/l to 25 mg/l P.

The Langmuir equation written in linear form (Olsen and Watanabe, 1957) is,

$$\frac{[P]}{x/m} = \frac{1}{Kb} + \frac{[P]}{b}$$

Where

[P] = equilibrium or final concentration of phosphorus,

x/m = weight of P adsorbed per unit weight of soil,

K = a constant,

b = the adsorption maximum, in the same units as x/m.

When one plots the straight line, $\frac{[P]}{x/m}$ vs. [P], the slope is equal to $\frac{1}{b}$ and $\frac{1}{Kb}$ is the intercept.

Ellis and Erickson (1969) made some simplifying assumptions and showed a simplified derivation applying the Langmuir equation to the case of phosphorus adsorption by soils. They used the equation with some experimental data in solving hypothetical problems in sewage disposal. By using another form of the Langmuir equation,

$$[P] = \frac{Q}{K(1 - Q)}$$

where Q = fraction of possible adsorption sites occupied by phosphorus, and other symbols are as above, data can be generated giving [P] vs. percent saturation of the adsorption maximum after K is found from the Langmuir plot.

Then given any specified limit on [P], this data can be used to determine the percent of the adsorption maximum (and thus how much phosphorus) can be taken up by the soil before that limit is reached in the outflow. The authors point out that the equation, $[P] = \frac{Q}{K(1 - Q)}$, has not been proven to be applicable to phosphate equilibrium. However, it provides for some interesting calculations and opens the way for the hope of more meaningful calculations if reliable data of the [P] vs. percent saturation type were available for a given soil area.

Previous Studies of Land Application Renovation

Land application of sewage is a very old practice, probably first done not only for disposal but for restoring the fertility of land. Application of sewage effluent to the soil for the purpose of tertiary treatment undoubtedly came along much more recently, but is certainly not by any means a new idea. Wilcox (1948) reported that Tucson and Phoenix, Arizona; Lubbock, Texas, Denver, Colorado, and Pomona, Whittier, and Riverside, California; used sewage effluent for irrigation. Also mentioned in a report by Merz (1956) were Bakersfield, Fresno, Wasco, and Tulare, California; and Abilene, Kingsville, and San Antonio, Texas. As of 1966, California had a total of 199 sewage plants that applied effluent to land, Texas had 40, Arizona 22, and New Mexico 21 (Eastman, 1967).

Studies of land renovation of effluents with respect to phosphorus

have shown varying degrees of success. Data from field studies of test spreading basins at Whittier Narrows and the Rio Hondo, California, and observation wells at Whittier Narrows, California, indicate that after about a year and a half of spreading, phosphorus had exceeded the soils' capacity to fix it and hence had significantly contaminated somewhere between 6 and 8 feet of soil depth. Although a direct comparison was not possible because of different input concentrations, the data suggested that the tight loamy soil at the Whittier Narrows spreading basin was removing far more of the added phosphate than the permeable fine to medium sand found at the Rio Hondo spreading basin. It also suggested that nearly all of the total phosphate moving down through the soil profile in both test basins was orthophosphate. The observation wells showed that the ground water at that time had not yet been significantly contaminated with phosphorus (McMichael and McKee, 1966). At Detroit Lakes, Minnesota, after three years of high rate irrigation with effluent, a test well showed phosphorus in the ground water had increased from 0.6 mg/l to 2.9 mg/l as P (Larson, 1961). It was noted that the soil in this case consisted essentially of gravel to a depth of 12 feet. Krone, McGauhey, and Gotaas (1957), in a three year study in California in which effluent was injected directly into a confined aquifer composed of sand and pea gravel, found that dissolved phosphates seemed to travel as freely as fluorescein tracer.

Greenberg and McGauhey (1955) found rather intermediate sucess in that for intermittent effluent spreading applications over a sandy loam

for a year and a half, nearly all the phosphorus was removed in the top one or two feet of soil. However, for continuous submergence, phosphorus contamination reached depths of over seven feet. They attributed this difference to the fact that biological activity was greatly increased during intermittent applications. Another consideration might be that phosphate precipitation is enhanced by intermittent applications. Whatever the cause, this is an indication that the method of application does make a difference.

Henry et al., (1954), in a three year field and lysimeter study of effluent irrigation in which they grew and harvested Reed Canary grass, found virtually no phosphorus in the percolate from 48 inch depth lysimeters of peat and silt loam soils or in samples from wells and from an adjacent stream. Also Sopper (1968), in the Pennsylvania State study, reported that between 89% and 96% of the applied phosphorus continued to be removed by a 48 inch depth of soil after three years of irrigation with effluent. Both of these studies stressed the importance of intermittent applications to maintain aerobic conditions in the soil, along with the growth of some plant cover.

Summary

All evidence in the literature indicates that phosphorus fixation in soils is complex. The reactions are complicated by the highly variable nature of soils and the many compounds that can be formed. Soil characteristics such as pH, particle size, organic content, and type of clay

minerals affect phosphorus fixation. In acid soils the amount of soluble iron and aluminum is of major importance. For alkaline soils the amount of lime is usually very important. The pH is important in both types since it determines the solubilities of the minerals. The percent and type of clay is extremely important in both acid and alkaline soil. No generalizations can be made to predict the effect of organic matter on fixation. Other factors, such as concentration of added phosphorus, reaction time, and effects of other ions present in solution are also important in phosphorus fixation.

Two hypotheses have been used to explain the actual mechanism of phosphorus fixing in soils. One assumes solubility theory applies and that fixation is largely the result of phosphate precipitation. The other by use of the isotherm theory assumes fixation is primarily an adsorption type reaction. Examples of use of both theories have been presented.

Data from previous studies of land application have shown that phosphorus has been effectively removed in some cases and not removed in other instances. Most cases of low or non-removal have been on relatively sandy soils and/or with continuous (not intermittent) application of phosphorus-laden water.

Because soils are so variable and since fixation depends upon so many different factors, there appears to be no simple method for determining the fixing capacity of soils nor for assessing the pollution hazard to ground water as a result of use of phosphorus-laden effluents.

PROCEDURE

Current Phosphorus Status of Ground Water

Data search

In an attempt to determine what range of phosphorus concentrations might be found in the Great Basin ground waters of Utah, a search was made for existing published and unpublished information on that subject. The U. S. Geological Survey and the Utah State Division of Health were contacted to ascertain their activities in analyzing ground water samples for phosphorus content. Where data on the phosphate content were accompanied by data for other constituents, they were included in a scatter plot check to determine if any general correlation existed between the amount of phosphate in ground waters and the amounts of some other constituents, such as calcium, that were present.

Sample analysis

A cooperative arrangement was made with the U.S. Geological Survey whereby they gathered an additional ground water sample for phosphate analysis while sampling for their regular water quality network during 1969 and 1970. In exchange, the results of the phosphate analyses on those samples done by this project were sent back to the U.S. Geological Survey.

The samples were analyzed by the Murphy-Riley (1962) colorimetric procedure for dissolved orthophosphate, using a Beckman Model B spectrophotometer with a sample cuvette having a 5 centimeter light path. This instrument was adequate to measure the low phosphorus concentrations often found in ground waters.

Determination of Disposal Capacity of Soils

Samples

In order to develop a procedure for determining the potential "phosphorus disposal capacity" of soils, and at the same time to determine that capacity for some major Great Basin soils, five soils were sampled on the bases of major acreages, potential irrigated value, and range in physical and chemical characteristics. Preliminary screening was done on the basis of existing characterization data from type profiles of various Great Basin soils, and five were selected. Field samples were taken with shovels and a 4 inch bucket auger as near as possible to the selected type locations, and of horizons conforming to those of the original type profiles. The samples were then air dried in the laboratory and ground to pass a 2 millimeter sieve. All rocks retained on a number 4 sieve were removed prior to grinding, and the grinders employed were such that most of the rocks above 2 millimeter size were discarded rather than crushed.

Soil columns

After considerable preliminary experimentation, the soil columns

were designed as shown in Figure 2. A known weight (600 grams) of air dry minus 2 millimeter soil was packed in with a piston-type packer made to exactly fit the 10.1 centimeter diameter plastic tube. If the column was a composite, simulating the soil profile, the layers were made by weight proportional to the horizon thicknesses and were separated by single sheets of Munktell's OK acid washed filter paper. If the column simulated a single layer, at least three equal layers were formed, separated by filter paper. This practice of using filter papers was adopted to eliminate problems of channeling in the columns and was found to be effective.

The columns were kept under continuous submergence under a constant head of about 14.5 centimeters. Flow rates were regulated in columns number 1 through number 7 by pin-pricking holes in the filter paper over the outlet as needed. For columns 8 and 9, tygon plastic tubing and an adjustable clamp on the outlet regulated the flow rates. The effluent applied was taken from the discharge of the city sewage lagoons at Logan, Utah, and enough $Ca(H_2PO_4)_2$ was added to bring the phosphorus (dissolved orthophosphate) concentration from about 2.5 mg/l P up to 10 mg/l as P. A preliminary check on total phosphorus revealed that the effluent contained essentially only orthophosphate. This was felt to be a good round figure for phosphorus concentration which would be representative of the average sewage effluent. The city effluent was used not only to simulate reality but also to eliminate soil dispersion problems encountered when using tap water phosphate solutions.

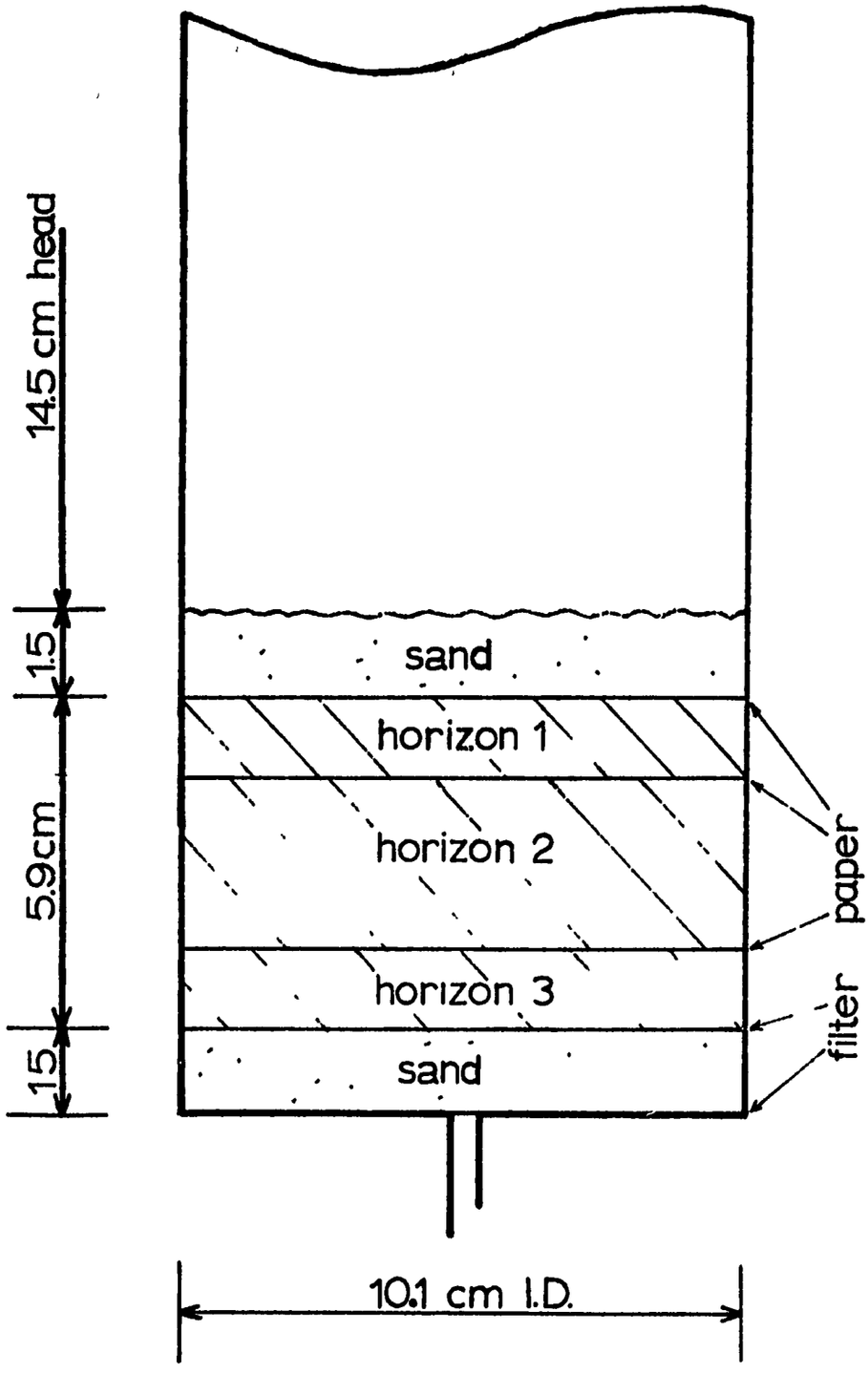


Figure 2. Design of Soil Columns.

Percolate samples were taken utilizing a fraction collector equipped with a 20 milliliter automatic siphon. Volume versus time measurements were kept. Care was taken to retard evaporation and microbiological activity by dumping samples from the fraction collector often and keeping them capped and in a dark drawer. If the samples were to be stored longer than a few hours, chloroform was added to inhibit biological activity. Samples were analyzed by the Murphy-Riley (1962) procedure, using a Bausch and Lomb Spectronic 20 spectrophotometer.

Breakthrough curves were then plotted for the columns as mg/l P in the percolate versus the output volume in milliliters. The area under such a curve represents the output of orthophosphate (in micrograms P) from the column. The input (in micrograms P) of orthophosphate to the system is simply the input P concentration (10 mg/l) times the throughput volume in milliliters. Then given any limiting P concentration in the outflow, the corresponding output volume point can be located on the column curve, and the total P retention calculated up to that point by subtracting output P from input P. Since the weight of soil in the columns was known, P retention (micrograms P per gram of soil) was calculated for each of the soils at output concentrations of 0.5, 1, 4, and 5.5 mg/l P and the soils were thus compared.

Repeated adsorption test

This test was devised as an extension of the often-used equilibrium phosphorus test, wherein the phosphorus adsorption isotherm is

obtained. In an attempt to reconstruct what happens in nature when a phosphorus-laden effluent is applied to a soil, it was realized that the conventional equilibrium test must be inadequate.

In nature the increments of soil, except for the extreme top layer, must equilibrate with gradually increasing phosphorus concentrations from the presumably low phosphorus concentration in the soil solution initially up to, if application is carried on long enough, that concentration which is being applied. The adsorption isotherm test supposedly shows, by obtaining adsorption amounts over a range of equilibrium phosphorus values, the maximum amount of phosphorus that can be adsorbed by a given soil. However, it is obtained by a single application over a range of equilibrium concentrations. Thus it takes no account of the behavior of a soil increment that has been equilibrated previously with phosphorus and has some prior phosphorus loading, and gives adsorption data only as a function of equilibrium concentration. The reason for the following procedure was, then, to obtain data on phosphorus retention not only as a function of equilibrium phosphorus concentration, but also as a function of the soil's previous loading with phosphorus.

Three-gram samples of air dry minus 2 millimeter soil were weighed into 50 milliliter centrifuge tubes. Thirty milliliter K_2HPO_4 solutions 0.01 molar in $CaCl_2$, and containing 1, 2.5, 5, 10, 15, and 20 mg/l as P were added to a set of duplicate samples, making a total of 12 tubes for each soil horizon tested. The phosphating solutions were formed by mixing, at the time of addition to the soil, 15 milliliters of

0.02 molar $CaCl_2$ solution and 15 milliliters of K_2HPO_4 stock solution containing, respectively, 2, 5, 10, 20, 30 and 40 mg/l as P. This procedure was carried out in the late afternoon. Then the tubes were sealed and placed in a reciprocating shaker overnight. The next morning the tubes were centrifuged at 3100 g's for five minutes, samples of equilibrated solution were withdrawn and analyzed for orthophosphate content by the Murphy-Riley (1962) procedure, and the remaining equilibrated solution was carefully decanted off. Finally, the tubes were weighed (tube tares were recorded beforehand) to determine the amount of solution retained in the wet soil. The tubes were then covered until late afternoon when the procedure of adding solutions and shaking was repeated.

In this overnight shaking process the equilibration time was from 16 to 17 hours. The phosphate adsorbed was assumed to be equal to the initial micrograms of P minus the final micrograms of P in the equilibrated solution, after both of the latter quantities were corrected for the amount of solution remaining in the soil after decantation. Cumulative amounts of adsorption (loading) were calculated and carried along with each run. Plots (see Appendix C) were made of adsorption (y) versus loading (x_2) at various initial concentration (x_1) values. Runs were carried out on each soil until the adsorption either dropped to zero or reached some stable value. Generally around 14 days was sufficient for this to occur, although some were run as long as 29 days. Five horizons, or 60 tubes, were run at one time, and the procedure was repeated on five separate soil profiles.

The above-described repeated adsorption test was also run on one soil horizon using a shaking time of 45 minutes and hence a total turn-around time of just over an hour. This particular test was carried on for seven runs. It was conducted to determine if extremely rapid loading would change the rate of adsorption decline.

A time-adsorption test was run on two soil horizons. In this test, duplicate samples were run for each horizon using only a 10 mg/l P, 0.01 molar $CaCl_2$ solution, but analyzing and calculating the adsorption after shaking for 0.5, 1, 2, 4, 8, and 24 hours. This was done to show the contrasting adsorption behavior between two soils that showed large differences in the repeated adsorption test.

Computer program

In trying to utilize the repeated adsorption data to solve an actual disposal capacity problem in phosphorus water application, it was envisioned to set up the soil model as a series of finite thickness (t) soil increments of unit width and depth. Also, the water, polluted with a given concentration of phosphorus, was to be applied in a series of finite volume increments. For example, a 10 mg/l P water increment (WINC) of 50 milliliters was applied to the soil surface. Soil increment number 1 (SINC1), being of some finite volume (t) and some given bulk density (b), contained bt grams of soil. Initially phosphorus loading (x_2) was assumed to be zero. Hence, for SINC1, going into the repeated adsorption curves (see Appendix C) an adsorption value (y) could be picked for $x_1 = 10$ mg/l

and $x_2 = 0$. If the total adsorption for SINC1 (y micrograms P per gram of soil times bt grams of soil) was greater than the amount of P in WINC1 (10 micrograms P per ml. times 50 ml.), no phosphorus went into SINC2. Then for WINC2, another y value was picked corresponding to $x_1 = 10$ mg/l and $x_2 = \frac{500}{bt}$ micrograms P per gram of soil. If the new y value had decreased enough so that the total adsorption (ybt) was now less than 500 micrograms P (that amount of P in WINC2), the remaining P above and beyond ybt went into SINC2. It was contained in 50 ml. of water (WINC2) and hence a new, lower x_1 was calculated for SINC2. The curves were entered again and a y value corresponding to the lower x_1, and to $x_2 = 0$ was picked. If this y happened to be sufficiently low, some of the remaining phosphorus went on into SINC3, etc. Obviously, after a few WINC's had been added, every SINC was in some different x_1 and x_2 state and hence y values were also changing throughout.

This type problem is a classic to be solved by computer methods and assistance was obtained to help write the program. The finished program (see Appendix D) requires initial data input of y versus x_2 values at various x_1 levels, i.e., data from the repeated adsorption test for each soil to be considered. Data for more than one soil may be inserted at one time if the control cards are properly advised. This saves read-in time for the program if more than one soil will be considered.

For each test, control card input must contain given values for test number, x_1 applied in mg/l, WINC in milliliters, SINC (called

sub-layer in the program) thickness in inches, main layer thicknesses in inches, number of main layers, a bulk density in grams per cubic centimeter for each main layer, a limiting P concentration in mg/l specified for the outflow, and a code number specifying if a new soil is to be considered for that test. Sample control and data input cards are shown, along with an example, in Appendix E.

Output from the program gives first a statement of the test conditions, then a printout of existing loading (x_2) and concentration (x_1) conditions at the sublayer (SINC) level each time phosphorus first passes from one main layer to the next, and also when the specified limiting concentration is reached in the outflow. There is also printout of the total quantity of water added at each of the above-mentioned printout points. The program also contains a convergence check and will print out "system not convergent in layer ( )" if the data is such that the adsorption value from the curve remains higher than the input amount of phosphorus. Some sample output is also included in Appendix E.

Supporting characterization information

In order to determine the physical and chemical properties of the soils that were related to phosphorus fixation the following tests were conducted on samples from each horizon studied in the five soils: ethylene glycol surface area (Bower and Gschwend, 1952), phosphorus adsorption maximum (Olsen and Watanabe, 1957), percent organic matter (organic carbon method) (Jackson, 1958), pH of saturated paste ("Diagnosis

and Improvement of Saline and Alkali Soils," USDA Handbook 60, 1954), cation exchange capacity ("Cation Exchange Capacity by Sodium Saturation," Agronomy Monograph Series 9, 1965), percent lime ("Carbonate in Soils," Agronomy Monograph Series 9, 1965), sodium bicarbonate soluble P (Watanabe and Olsen, 1965), and mechanical analysis by hydrometer ("Grain-Size Analysis," ASTM, 1964). The phosphorus adsorption maximum and ethylene glycol surface area tests were performed by this author, while other routine tests were made by the Utah State University Soil Testing Laboratory.

RESULTS AND DISCUSSION

Current Phosphorus Status of Ground Water

Data search

Limited data was found on the orthophosphate content of Utah's Great Basin ground waters. Personal communication with U.S. Geological Survey personnel revealed that phosphate analyses on well samples were not made except in rare cases of specialized assignments. To their knowledge, the only such paper in recent history containing several phosphate analyses of well samples in the study area was written by K. M. Waddell in 1967. This contained data on 33 samples from wells and springs in the Sink, Skull, Rush, Government Creek, and Dugway Valleys. The results are listed in Appendix A. The highest phosphate concentration was found in a sample from a well in Sink Valley where the concentration was 0.29 mg/l as P. A sample from a well just east of the Lakeside Mountains tested 0.16 mg/l as P, a well inside the Skull Valley drainage contained 0.08 mg/l P, and a spring in Government Creek Valley contained 0.08 mg/l P. All others contained less phosphate, with the overall average being 0.025 mg/l as P.

It is of interest to note that by calculating average values for $[H^+]$ and for the different ionic concentrations over the entire 33 analyses, and also assuming an equilibrium with the stable phase hydroxyapatite

would be reached, using the equation from page 15.the average phosphate content of these ground waters should be 0.0057 mg/l as P. When octocalcium phosphate was assumed to be present, the theoretical average was 3.3 mg/l as P. A similar calculation for the Sink Valley well which had the highest actual concentration at 0.29 mg/l P showed that it should theoretically contain 0.17 mg/l as P if hydroxyapatite was assumed to be present. Whether these calculations are meaningful depends mostly on the assumption that hydroxyapatite is present as a stable phosphate phase, but the nearness of agreement between the actual and theoretical values lends some credence to this assumption. This might serve as a basis for holding suspect any sample from this or a geologically similar area which showed a phosphate concentration substantially in excess of this range of values. It is possible that values above those for equilibrium with hydroxyapatite are an indication of pollution or that the samples have been contaminated. Similar calculations could be made for areas where the geology and soils dictate that strengite or variscite would probably be the stable phosphates present. More research in some different ground water basins would be very desirable to test this theory.

The Utah State Division of Health has published results of numerous phosphate analyses of well samples in their annual tabulations, from 1964 through 1970, of "Water, Wastewater--Chemical and Radiological Analyses." These are listed in Appendix A. Within the area of this study they have made 691 analyses. The results of these tend on

an average to run nearly an order of magnitude higher than either the U.S. Geological Survey or the analyses run by this project. The values show a very large range, from 0.00 mg/l P to 12.0 mg/l P, with the average value being 0.27 mg/l P. Some of the higher values are definitely suspect, as they show ground waters higher in phosphate than many sewage effluents. These would indicate that the samples were contaminated during collection, transport, or analysis, or else that extreme pollution of the ground water has actually occurred. Rechecks of all the values of 0.5 mg/l P and higher would seem to be in order. Upon checking, it was found that 13 of the highest samples have been resampled and analyzed by the Division of Health. Of these, the highest, which originally contained 8.3 mg/l P, rechecked at 0.33 mg/l P. The next highest, 2.7 mg/l P, rechecked at 0.13 mg/l P. However, two of the samples which originally tested at 0.40 mg/l P were rechecked at 1.87 and 1.80 mg/l P, and then again at 0.03 and 0.07 mg/l P, so there is still some uncertainty about the actual amounts of phosphate present. Some more rechecks with special care being taken to prevent any possible sample contamination would be of interest.

The scatter plots resulting from the U.S. Geological Survey data (Waddell, 1967) are shown in Appendix A. The scatter plots from the Utah Division of Health data are not shown because uncertainty about some of the phosphate concentrations made it too difficult to point out any basic trends. There appears to be no relationship between the

amount of phosphate and any other constituent present in ground water, except possibly in the case of calcium and magnesium. In this plot, (Figure 3), it appears that the very highest phosphate amounts tend to occur only in the lower ranges of Ca + Mg. From a consideration of the common ion effect on any calcium phosphates, such as hydroxyapatite, this tendency would be expected in the case of Ca and Mg.

Sample analysis

One hundred fifty samples of ground water gathered by the U.S. Geological Survey from around the study area were analyzed by the author. The results are shown in Appendix A. The values were generally very low, ranging from 0.00 mg/l P to 0.93 mg/l P and averaging 0.028 mg/l P. This is an order of magnitude less than those values reported by the Utah Division of Health. Random resamples were collected a year apart for 30 of the samples, and agreement was excellent. Disagreement by more than 0.0167 mg/l as P was present in only five of the rechecks, with the greatest difference being only 0.04 mg/l as P.

Areas that contained several samples somewhat higher than the average were: (a) the Weber delta area west of Ogden, contained in Townships 4 through 7 North and Ranges 2 and 3 West (Salt Lake Base Line and Meridian), (b) northwest of Delta in T. 16S, R. 8W,

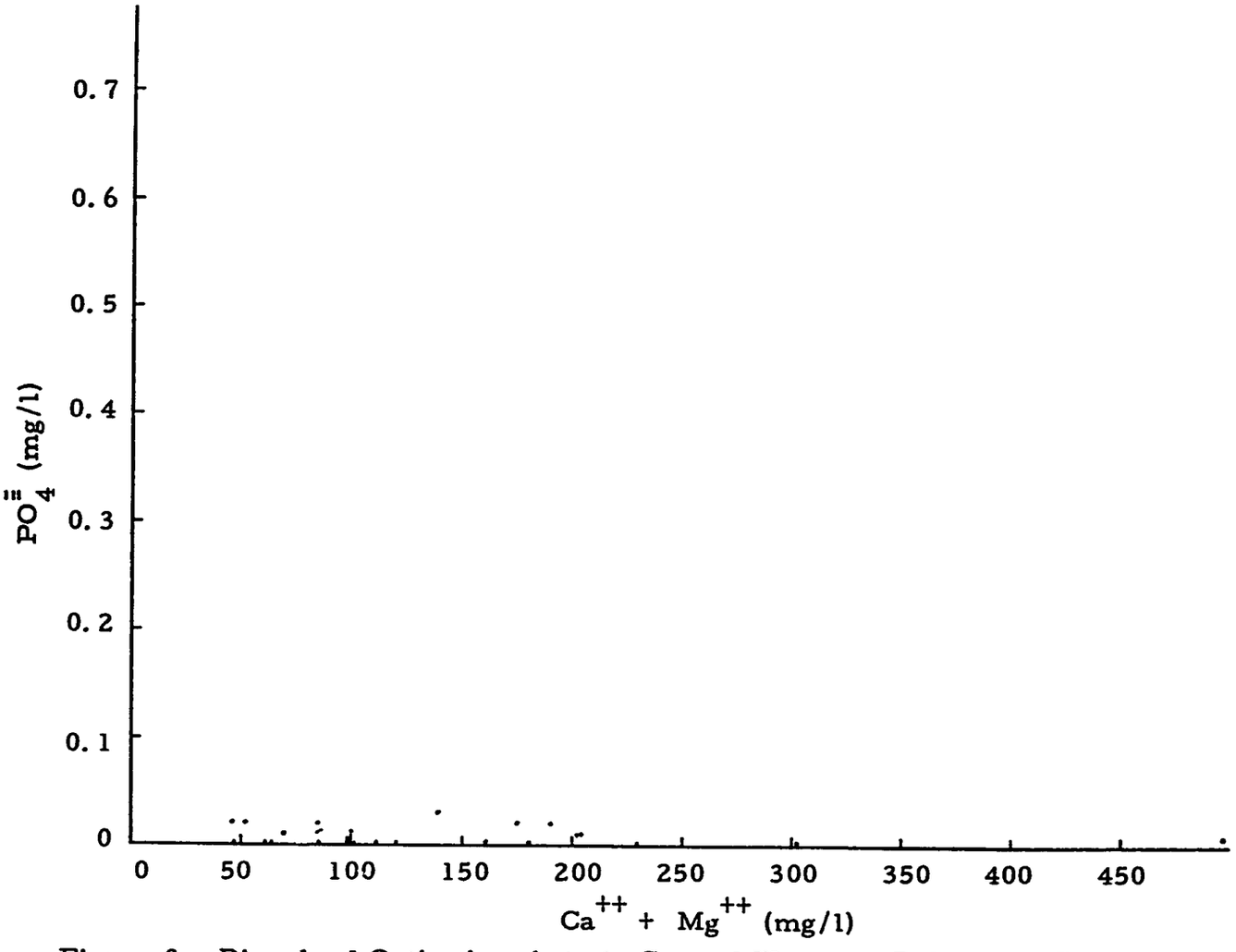


Figure 3. Dissolved Orthophosphate in Ground Water as Related to Calcium plus Magnesium Content. (Data from Waddell, 1967).

(c) south of Milford in T. 28 and 29 S, R. 10 and 11 W, (d) north of Enterprise in T. 36 S, R. 15 and 16 W. One thing that these areas seem to have obviously in common is that they are all in or very near old delta areas; the Weber delta, the Sevier delta at Delta, Beaver River at Milford, Shoal Creek at Enterprise. This brings up the possibility that some natural phosphorus from surface erosion may have been brought in and stored during the time of the relatively rapid deposition of the deltaic sediments.

Whatever the cause, the Weber delta area would seem to have special significance, both because it has the highest of the phosphate concentrations measured and also because its ground water could certainly serve as a direct nutrient source to fresh water areas such as Willard Bay. Further study in this area to determine whether the observed high concentrations are natural or the result of man's effects is desirable before any standards for phosphorus disposal are set for the area.

Determination of Disposal Capacity of Soils

Soil column curves

Much preliminary experimentation was done prior to obtaining reproducible data from the column percolation studies. Various sizes and shapes of columns containing different amounts of soil or soil and sand mixtures were tried. Initially, phosphorus input solutions were made up from either distilled or tap water but use of these solutions

caused severe soil dispersion problems in the heavier soils, such as Nibley. Another problem encountered occasionally was that of apparent channeling through the columns, causing erratic fluctuations in flow rates. However, after the columns were designed as shown in Figure 2 and the input solutions were made up from actual sewage effluent, the phosphorus breakthrough curves (Figure 4, see also Appendix B for data from additional profiles) were remarkably reproducible for a soil. Even when the flow rates through identical columns of the same soil were adjusted quite differently, as they were for replications of the percolation tests in the Warm Springs and Draper soils, the resulting breakthrough curves were essentially the same. This finding was felt to be a significant step towards being able to place confidence in any design values obtained from soil column tests.

Retention capacity from soil columns

The phosphorus retention capacity of any soil, before the phosphorus in the outflow reaches some given amount, can be found easily by using the phosphorus breakthrough curve. The area under the curve from zero percolate outflow to that amount of outflow where the limit concentration was reached is equal to the total amount of phosphorus output up to that point. In this case,

mg/l P in outflow x milliliters outflow = total micrograms P output.

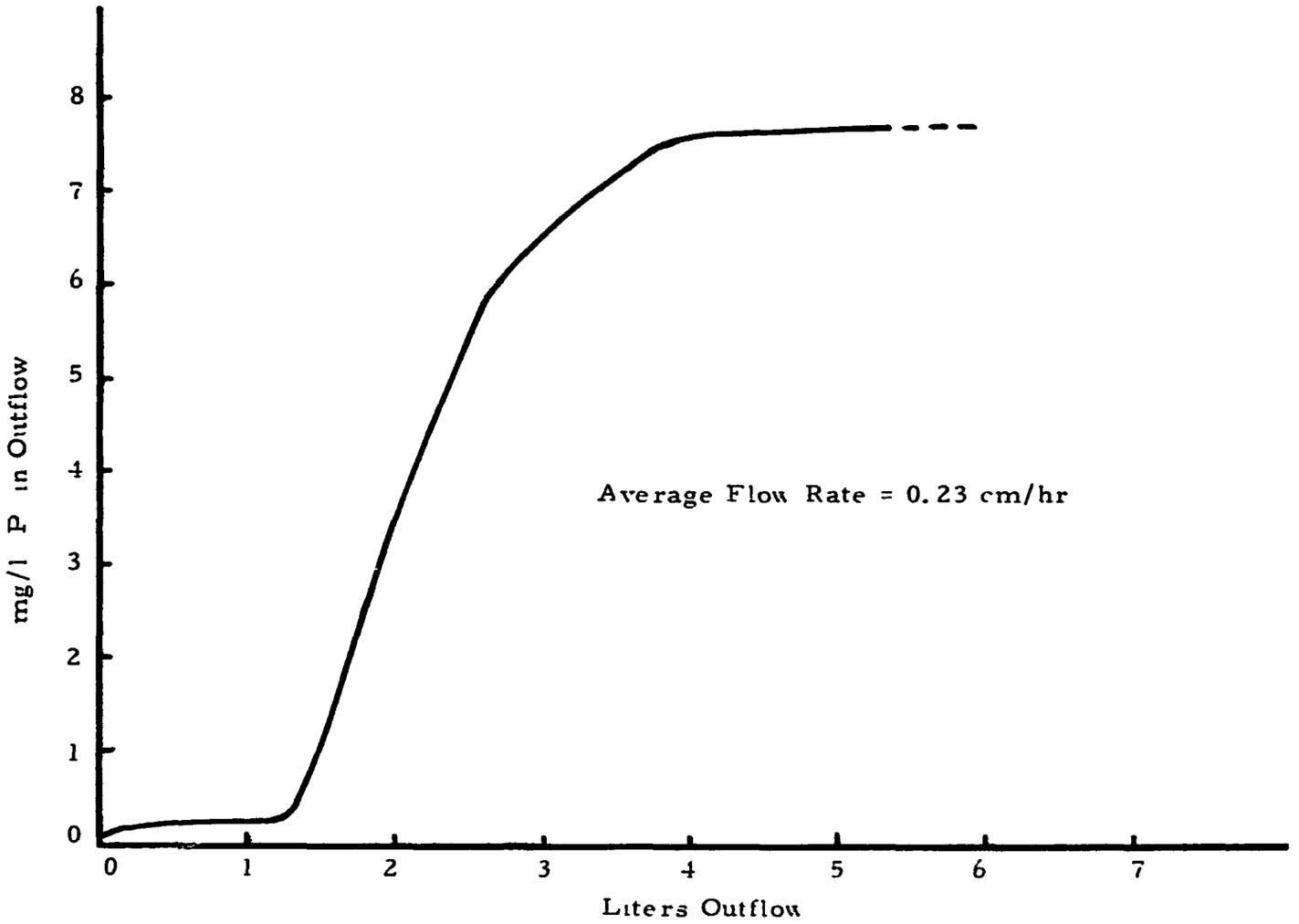


Figure 4. Phosphorus Breakthrough Curve from Soil Column Test 1, Warm Springs Soil Profile.

The total phosphorus input is equal to the input concentration multiplied by the percolate outflow (which equals fluid input) up to the point where the limit concentration was reached. In this case,

mg/l P in input x milliliters outflow = total micrograms P input.

Then, input P minus output P equals retained P, micrograms P in this case, and dividing by the known weight of soil in the column gives P retained per unit weight of soil. These values, easily converted to pounds P retained per acre foot of soil, are shown in Table 2. A final downward adjustment of the retention capacity can then be made if a large percentage of the soil volume is composed of particles larger than 2 millimeters. The retention capacity of such material is negligible. In this way the retention capacity value needed for designing to eliminate ground water pollution by phosphorus disposal over a soil area can be found. The phosphorus retention capacities up to a 0.5 mg/l P limit in the outflow and with a 10 mg/l P input ranged from 76 to 319 pounds P per acre-foot for the five Great Basin soils studied. If an average soil profile is assumed to be 5 feet in depth, the range in quantity of 10 mg/l P effluent that could be safely applied by continuous flooding over each acre of these soils would be from 4.56 to 19.15 million gallons.

It should be mentioned here that these values derived from the soil columns as designed in this study probably represent a minimum

Table 2. Phosphorus Retention Capacities (Pounds P per Acre-Foot of Soil) of Five Great Basin Soils at Various Limiting P Concentrations in the Outflow.

Soil Name	Limit 0.5 mg/l	Limit 1.0 mg/l	Limit 4.0 mg/l	Limit 5.5 mg/l
Warm Springs (profile)	76*	84*	111*	124*
Kilburn (profile)	92**	107**	157**	186**
Nibley (profile)	257	280	368	392
Nibley (0-7" only)	154	180	241	276
Parleys (profile)	282	298	347	399
Parleys (6-15" only)	0	0	159	184
Parleys (26-33" only)	395	410	471	495
Draper (profile)	319*	346*	484*	--

* Average of 2 tests
** Corrected for 50% of field volume > 2 mm. size.

estimate of the phosphorus retention capacity of the soil. These columns were subjected to continuous submergence, simulating the most severe application conditions as discussed earlier in the review of literature. Very little time was available for phosphate precipitation to occur. There was also no uptake of any phosphorus by vegetative cover, which was stressed as important in some of the literature cited. It would seem that in using soil column tests for determining the P fixing capacity of a soil, there should be repeated applications of P in order to obtain some measure of possible phosphorus precipitation.

Repeated adsorption tests

The results of the repeated adsorption tests (Figure 5, see also Appendix C for data from additional profiles) were somewhat surprising. It was anticipated beforehand that a soil's capacity to retain phosphorus would eventually decrease as the soil was more heavily loaded with phosphorus. This is an obvious assumption to make after observing the phosphorus breakthrough behavior in a soil column. Two of the soils, Draper (Figures 25-28) and Kilburn (Figures 5, 29, 30) showed this expected decrease, but the other three soils behaved quite differently.

The Parleys soil showed a rapid decrease in P retention capacity in the top two horizons (Figures 31-32) as the loading increased. The third horizon (Figure 33) showed rapidly decreasing P retention with increased loading up to a point, then the P retention began to

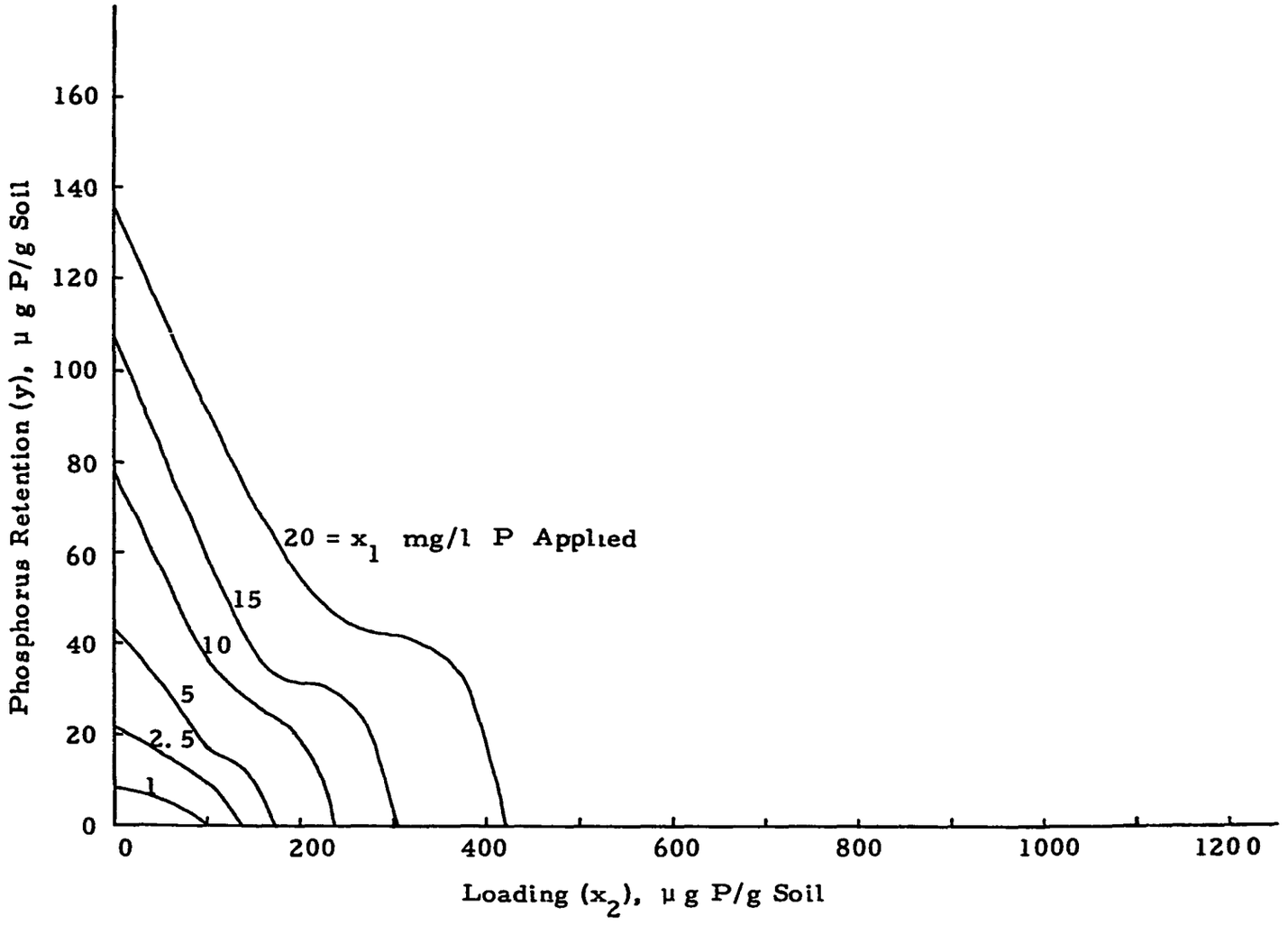


Figure 5. Repeated Adsorption Data for Kilburn 0-11 in. Horizon.

increase again and finally leveled off for the three highest applied concentrations of 10, 15, and 20 mg/l P. The two deepest horizons (Figures 34-35) showed progressively greater tendencies to increase in P retention as P loading increased, with the bottom horizon to which 20 mg/l P was applied actually showing an increase in P retention from the very start of loading.

The Nibley soil's top two horizons (Figures 36-37) showed P retention first decreasing rapidly, then for the 10, 15, and 20 mg/l P applications there was next an increase and finally another decrease in P retention as loading progressed. The third horizon (Figure 38) showed an initial decrease in P retention, followed by an increase and then a leveling off for the 10, 15, and 20 mg/l P applications. The two deepest horizons (Figures 39-40) were nearly identical to their Parleys counterparts discussed above.

The Warm Springs soil (Figures 41-42) showed the greatest tendency of all soils to increase P retention capacity as P loading increased, especially in the deeper horizons. Bearing these facts in mind while examining the soil characterization data in Table 3 will reveal a very strong correlation between a horizon's tendency to increase in P retention with increased loading and the lime content of the horizon. There is also a fair amount of negative correlation between this tendency and the percent organic matter and $NaHCO_3$-soluble P contained in the horizon. This negative correlation might be

Table 3. Characterization Data for the Five Soils Studied

Soil Name	Horizon	Langmuir P Ads. Max (μgP/g soil)	% OM (%)	pH (sat'd. paste)	CEC (meq/ 100g soil)	% $CaCO_3$ (%)	$NaHCO_3$-soluble P (mg/l P)	Mechanical Analysis Hydrometer S	Si	C	Text.	Surface Area (m^2/g soil)
Nibley	0- 7	231	2.98	8.0	25.2	1.7	15.0	8	66	26	SiL	179.6
	7-13	197	2.38	8.0	25.9	0.8	3.9	6	68	26	SiL	175.0
	13-20	192	1.28	8.0	23.7	7.2	2.4	0	55	45	SiC	185.0
	20-32	188	1.12	8.0	21.7	18.5	1.6	0	47	53	SiC	165.3
	32-43	191	0.64	8.1	18.5	33.2	1.4	0	54	46	SiC	151.0
Parleys	0- 6	220	3.78	7.3	17.3	0.5	69.0	41	38	21	L	95.2
	6-15	214	2.52	7.2	17.3	0.2	61.0	39	36	25	L	99.1
	15-26	181	1.05	7.5	18.5	5.2	8.2	24	44	32	CL	143.3
	26-33	177	1.00	8.1	12.7	28.2	4.5	25	52	23	SiL	80.5
	33-60	162	0.36	8.1	12.7	27.3	0.7	23	52	25	SiL	78.4
Kilburn	0-11	177	3.03	7.2	15.9	0.1	24.0	49	33	18	L	73.6
	11-24	154	1.16	7.0	11.2	0.1	18.0	63	25	12	SL	64.2
	24-60	83	1.02	6.9	10.4	0.2	15.0	65	24	11	SL	58.9
Warm Springs	0- 6	94	1.90	7.9	9.5	6.0	19.0	69	18	13	SL	52.9
	6-37	99	0.88	8.1	8.4	12.8	5.5	65	18	17	SL	53.1
	37-60	66	0.16	8.5	3.9	10.7	3.7	87	7	6	LS	24.9
Draper	0- 6	128	5.55	7.8	27.9	0.0	11.0	51	27	22	SCL	150.9
	6-16	116	5.13	7.8	27.7	0.0	3.7	54	29	17	SCL	148.6
	16-26	71	0.99	7.8	10.2	0.0	0.0	79	13	8	LS	57.2
	26-37	147	1.99	7.3	28.7	0.0	10.0	31	40	29	CL	154.5

expected in the case of $NaHCO_3$ - soluble P since when it is high, there is some indication that part of the soil's P retention capacity has already been used up.

This increase in P retention followed by a leveling off can probably be explained by assuming precipitation of calcium phosphates occurs, especially after some nuclei have formed. For those soils in which the increase occurred, the samples (especially those with 5, 10, 15, and 20 mg/l P initial concentration) tended to level off at some common equilibrium P concentration, which would indicate the formation of a solubility equilibrium. This common concentration was quite different, however, depending upon which soil horizon was considered. For example, the common equilibrium concentrations for the Warm Springs 6-37, 37-60, and Parleys 26-33, and 33-60 inch horizons averaged 0.80, 0.38, 2.30, and 0.89 mg/l P, respectively. Using solubility equations from page 15 along with approximate ion concentrations existing during the adsorption tests gives 3.8 mg/l P for the equilibrium concentration if dicalcium phosphate dihydrate is assumed to be present and 0.33 mg/l P if octocalcium phosphate is assumed to be present. On this basis, some intermediate compound is probably being formed. Certainly precipitation of calcium phosphates comes quickly to mind when considering the procedure of the test with regard to the tremendous amount of calcium and phosphate that is imposed upon each 3 grams of soil throughout the entire

test. However, it seems very puzzling that this precipitation would occur to such an extent in some soils, but apparently not at all in others. One way to answer the question might be to check the soil contents of the tubes under a microscope after several runs to detect the possible presence of calcium phosphate crystals.

Whatever, the cause, the potential usefulness of the test must be considered. Surely a test that seems to correlate so well, either negatively or positively, with some of the soil properties as discussed above should be a good indicator of the P retention capacity of a soil. By inspection alone, the soils which increase in P retention capacity with increased loading should be most desirable for retaining phosphorus from any applied source, and those which show a rapidly decreasing P retention capacity should be least effective.

By comparing the results of the repeated adsorption tests (Appendix C) with those of the column percolation studies (Appendix B) it can be seen that the two tests were in good agreement for Kilburn, Nibley, Parleys, and for two separate horizons within the Parleys profile. However, for the Warm Springs and Draper soils, the repeated adsorption test did not predict the phosphorus retention behavior as shown in the column tests. It is felt that somewhat better agreement would have been obtained had the columns been dosed intermittently, so that the effects of phosphate precipitation could have been better expressed in the columns.

It appears that the repeated adsorption test, with its emphasis on intermittent applications of phosphorus, will give a better measure of the maximum phosphorus retention capacity of a soil. This information will be of direct interest when it is desired to design from the standpoint of getting the maximum capacity from the soil for P disposal purposes. It also indicates the importance of the care which must be taken to apply the effluent intermittently if the emphasis is placed on getting the highest P disposal capacity from a limited soil area.

One modification of the repeated adsorption test procedure was tried in which the shaking time for equilibration was reduced from 16 hours to 45 minutes, making total turn-around time for a run about one hour. This was done to determine if precipitation as a fixation mechanism would be discouraged by a drastic reduction in the time available for the formation of calcium phosphates. As shown in Figure 6, there was an increase in P retention with increased loading, although P retention per gram of soil was initially much lower for the shorter interval. Several short interval repeat treatments were accomplished before the rate of fixation approached values as high as those for the longer treatment periods, shown in Figure 7.

Adsorption maximums

Even though it was felt (as discussed above in the Procedure section) that the phosphorus adsorption maximum from the Langmuir

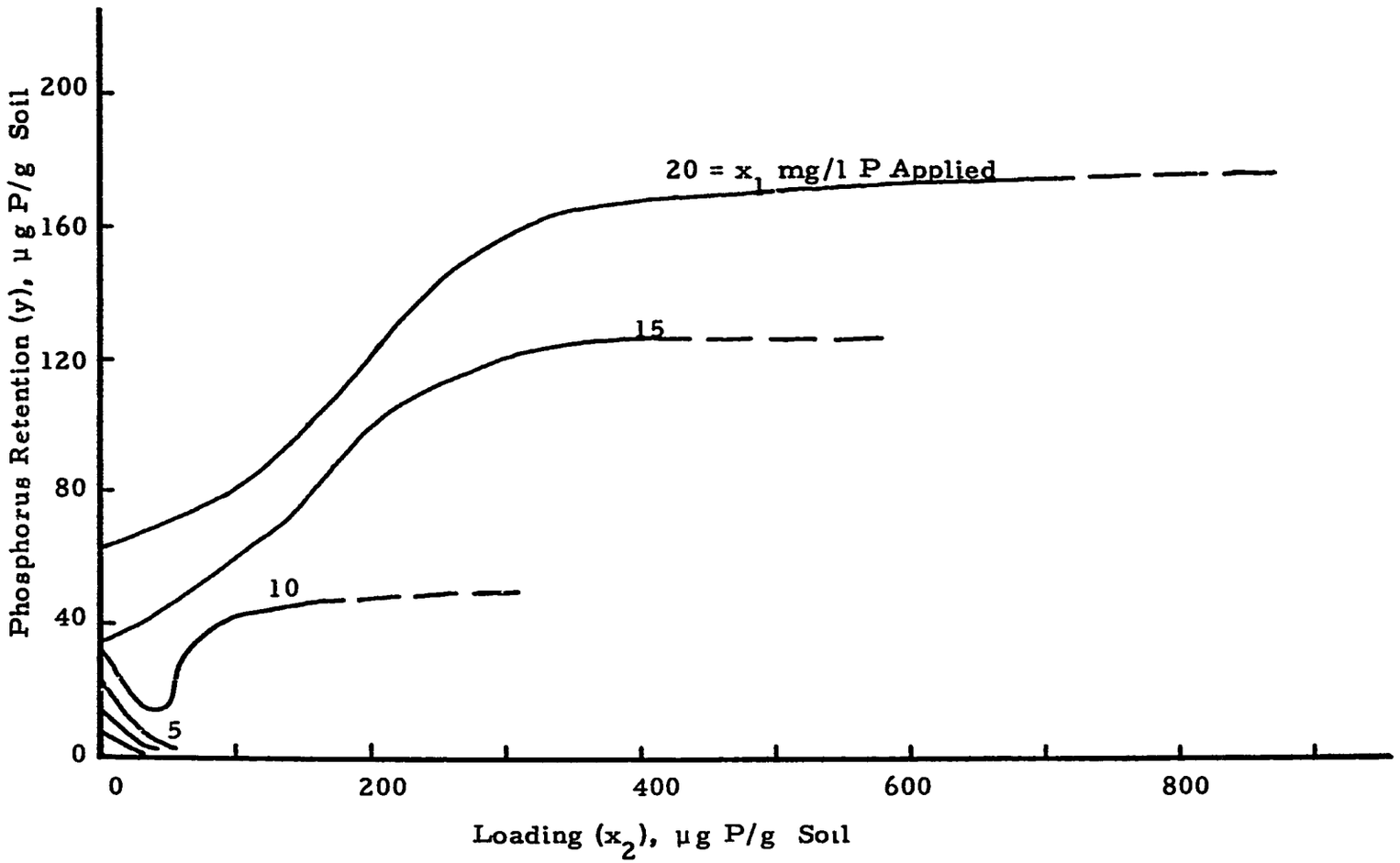


Figure 6. Repeated Adsorption Data for Warm Springs 37-60 in. Horizon. (One-Hour Runs).

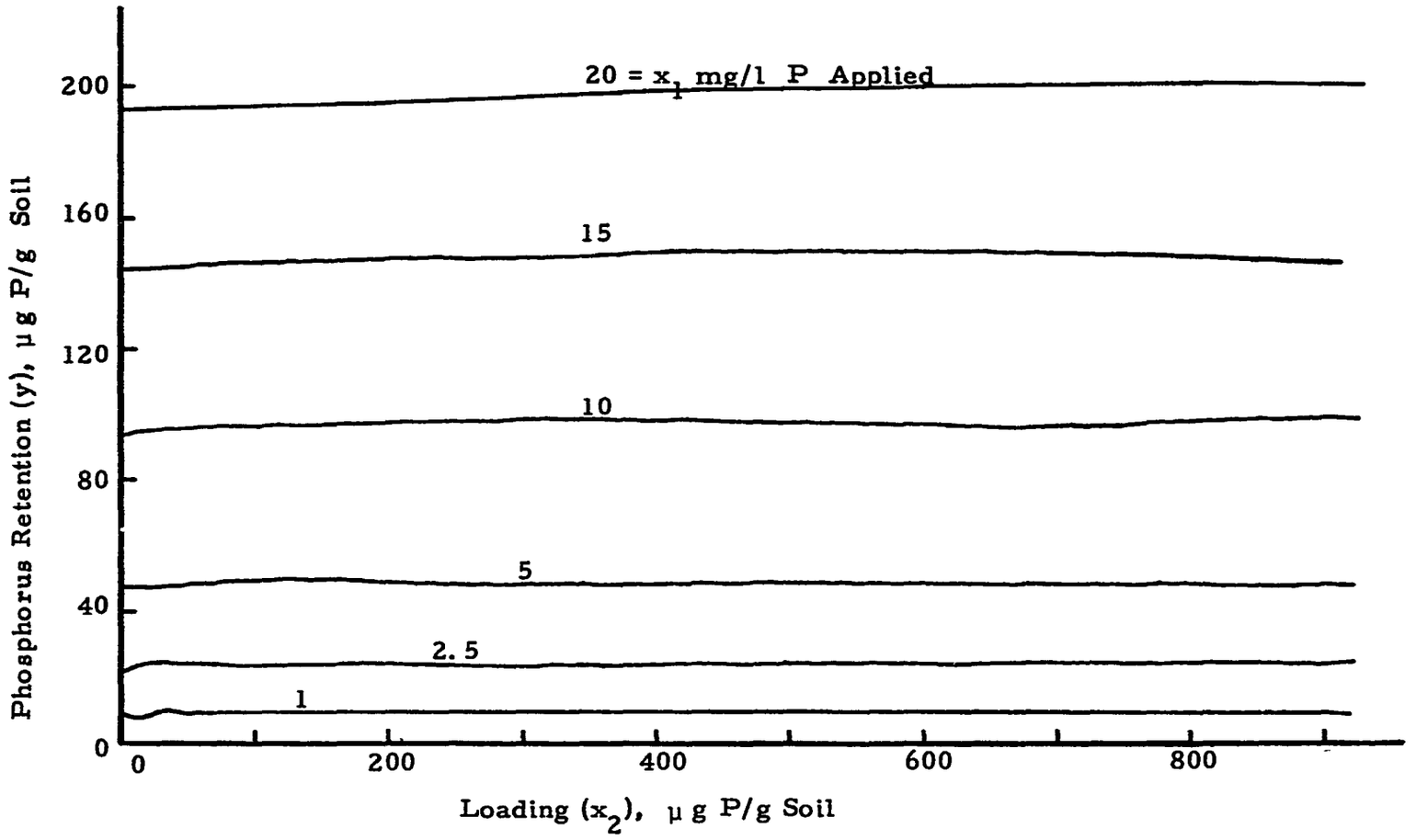


Figure 7. Repeated Adsorption Data for Warm Springs 37-60 in. Horizon. (16-Hour Runs).

isotherm was not the best way to directly obtain values for phosphorus retention capacity, the adsorption maximums were calculated and are shown in Table 3 to see if they would serve as a good indicator of what the actual phosphorus retention capacity of a soil might be. The required adsorption isotherm data for the Langmuir isotherm was already taken as the first run of the repeated adsorption test.

Upon examining the resulting Langmuir plots (Figure 8, see also Appendix C for data from additional profiles), additional problems with the adsorption maximum approach become evident. A sharp deviation from a straight line occurs at quite low equilibrium phosphorus concentrations ranging from 0.3 mg/l to 8.5 mg/l P in these soils. This deviation has been observed by other researchers (Cole, Olsen, and Scott, 1953; Edwards, 1968; Olsen and Watanabe, 1957, Rennie and McKercher, 1959; Weir and Soper, 1962) but generally was found to occur at somewhat higher equilibrium concentrations, in the range of 15 to 25 mg/l P. It has been thought by most to be due to a precipitation reaction. In any case, for soils such as those examined in this study, the deviation from the Langmuir straight line occurs within the range of equilibrium concentrations that will undoubtedly be attained in any sewage application to the soil. Hence it would seem in this case that little confidence could be placed in any adsorption maximum value that was obtained from the slope of the Langmuir isotherm, because the test P concentrations would not be representative of the anticipated natural conditions.

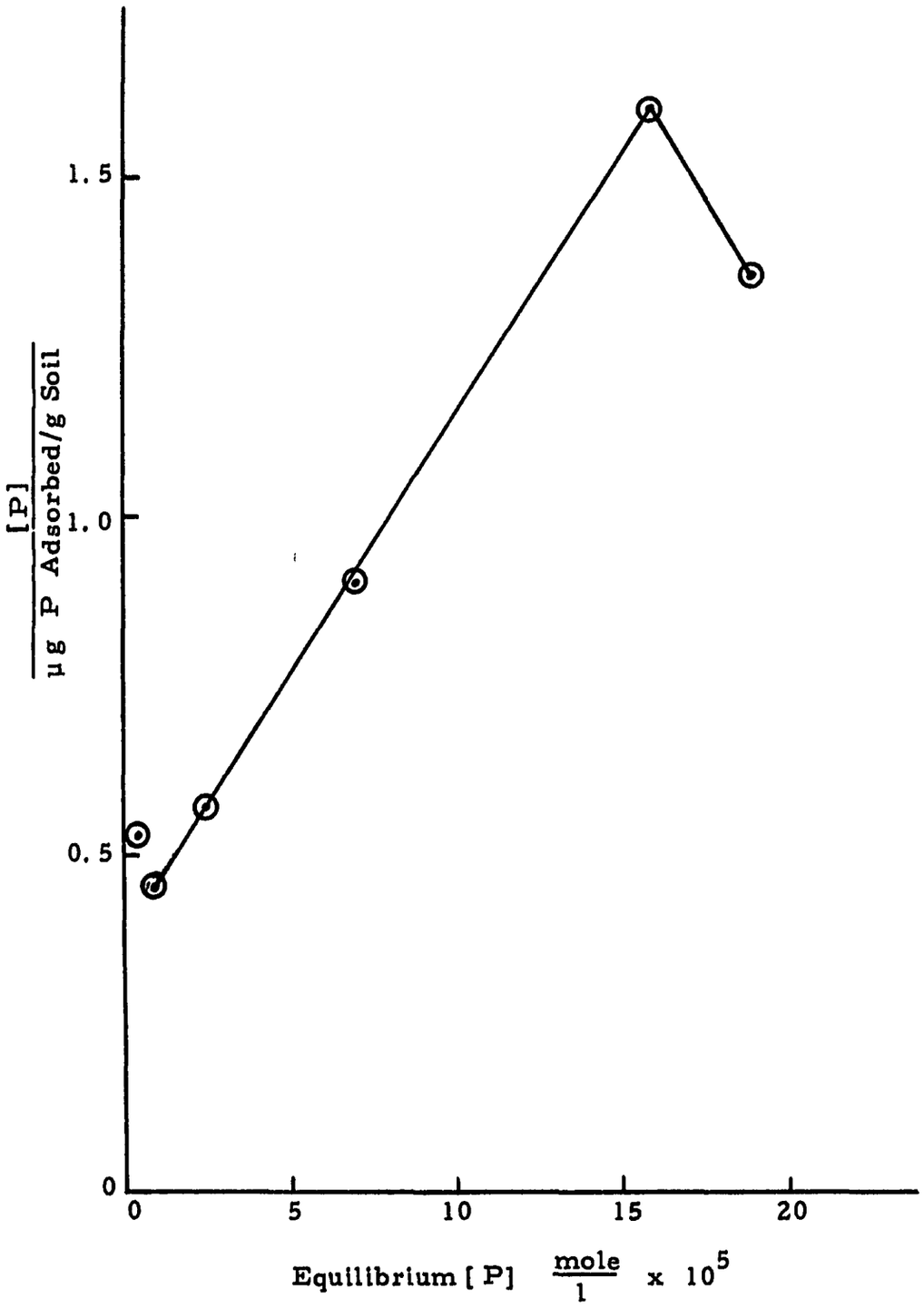


Figure 8. Langmuir Isotherm for Draper 0-6 in. Horizon.

It is interesting that the results of the first run adsorption do show a definite trend of the deeper soil horizons to be more efficient in adsorbing phosphorus. That is, even though the Langmuir adsorption maximums are somewhat less, the deeper horizons attain a greater percentage saturation of their maximums without allowing the equilibrium phosphorus concentration to become as high. This is shown graphically in Figure 9, see also Appendix C for data from additional profiles.

Another problem is pointed out by examining the results of the time-adsorption test (Figure 10). This shows that phosphorus adsorption (or retention might be more accurate) behavior can be quite different for different soils. The Draper soil is a classic example of what most researchers consider true adsorption to be--a rapidly occurring reaction in which most of the retention takes place within a half-hour, and nearly all of it within two hours. The Warm Springs soil, on the other hand, shows no clear-cut break between adsorption and any precipitation that occurs. The retention does occur rapidly enough, however, that a short half-hour or one hour equilibration test designed to pick up only the adsorption part of the P retention would miss a considerable part of the actual phosphorus retention capacity of such a soil. Comparing the two curves in Figure 11 reveals the difference in the Langmuir isotherms obtained for that soil with 45 minutes' and 16 hours' equilibration time. So, for some soils such as the Warm Springs, adsorption tests such as the

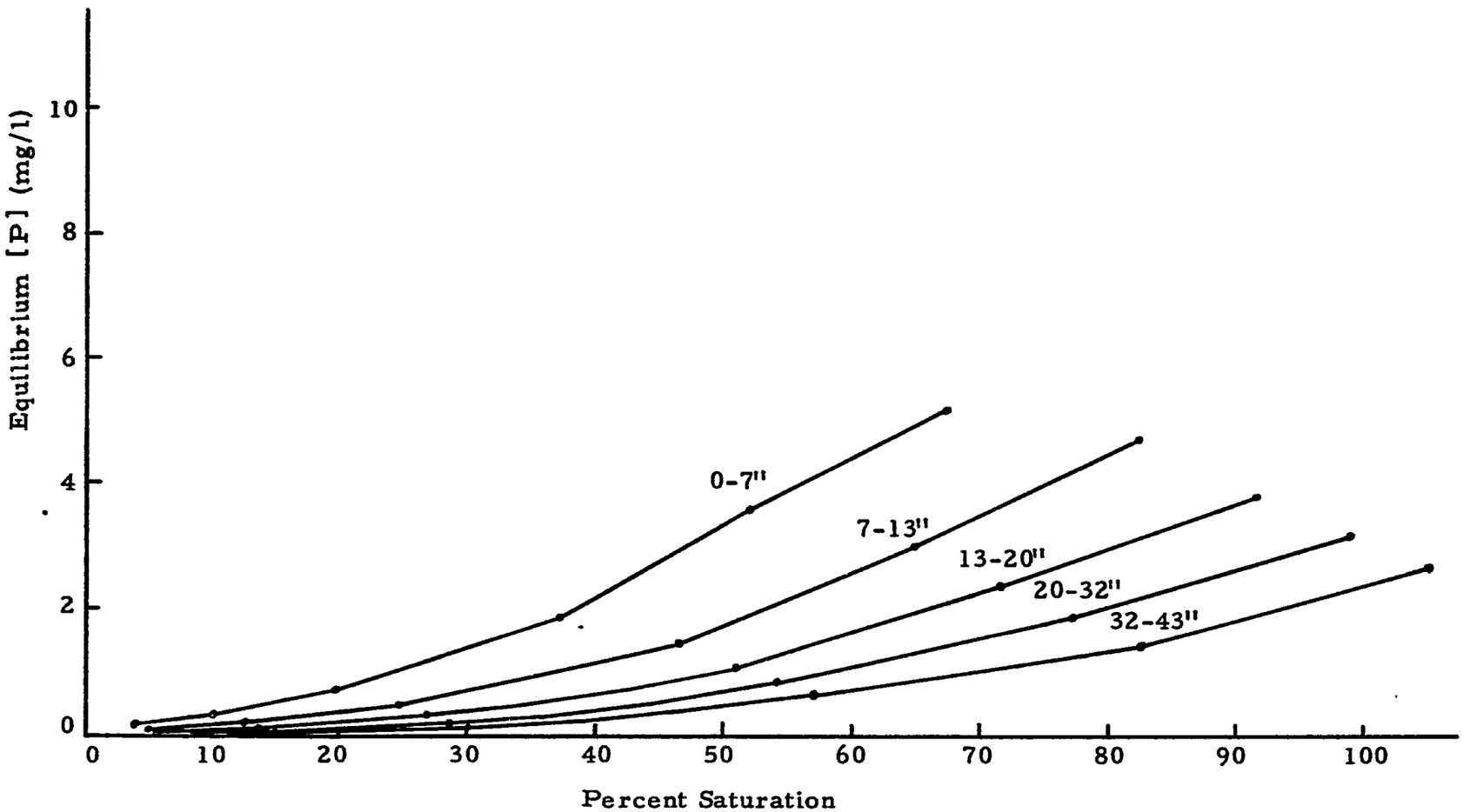


Figure 9. Equilibrium [P] versus Percent Saturation of Langmuir Adsorption Maximum for Nibley Horizons.

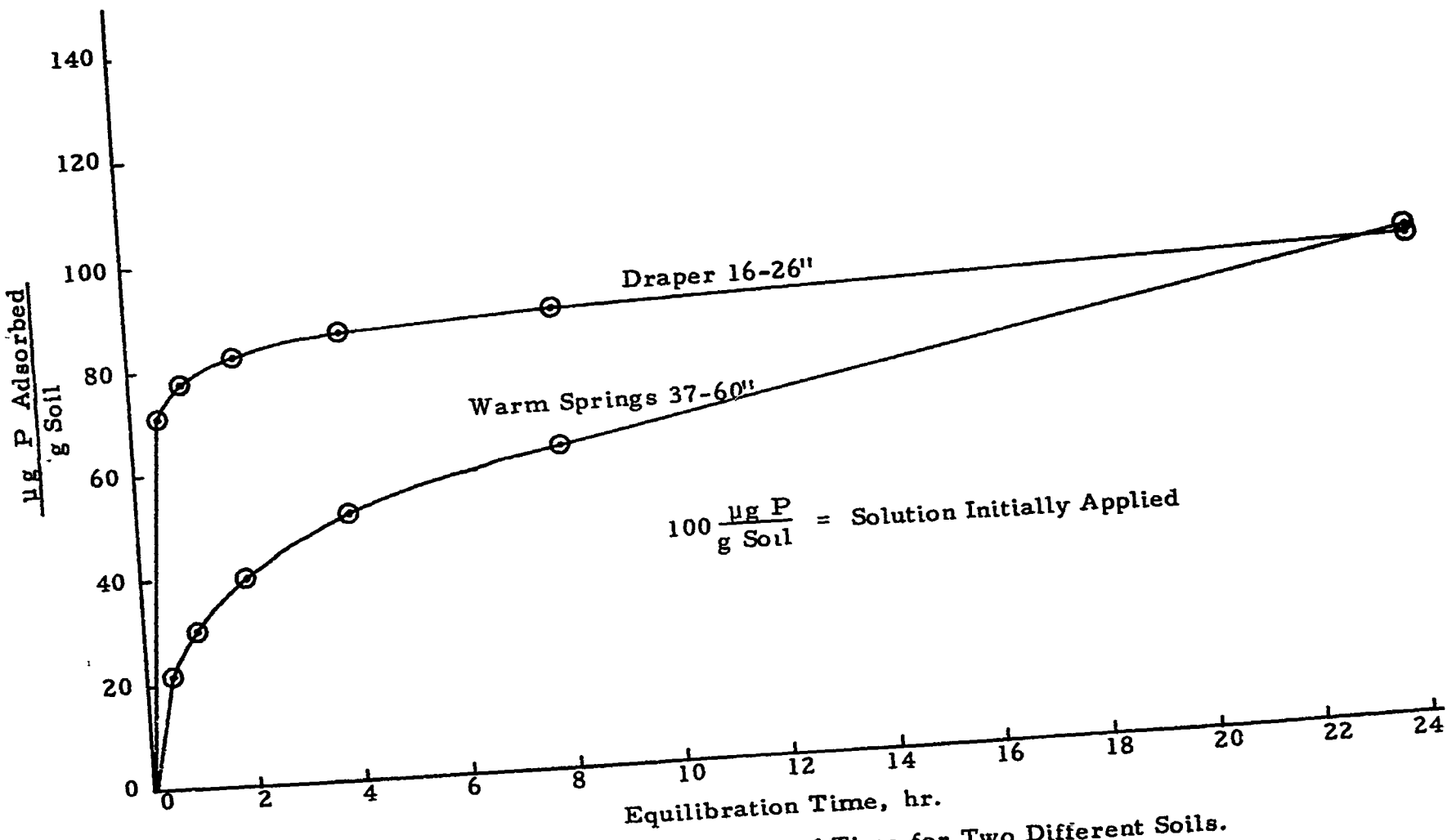
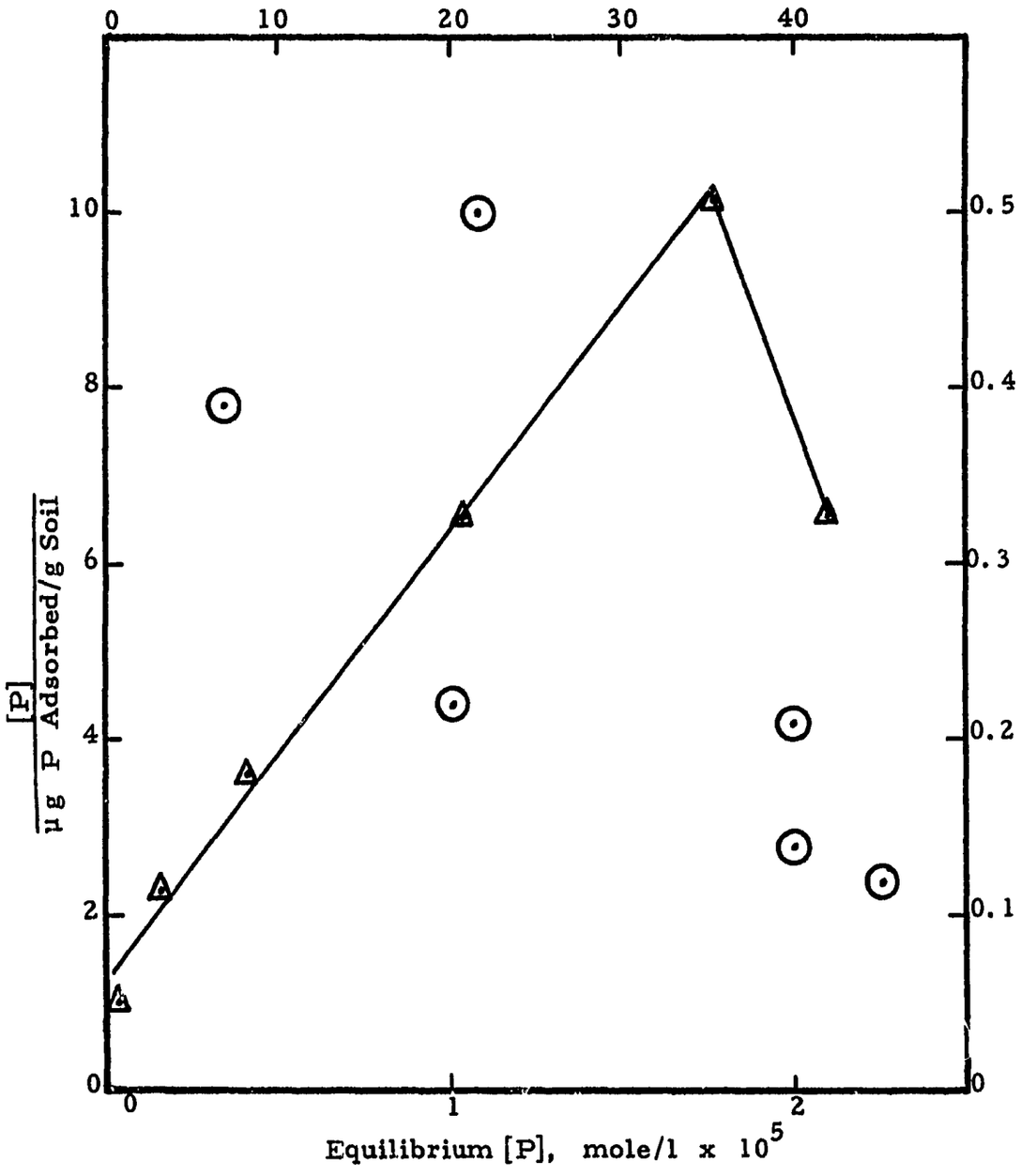


Figure 10. Phosphorus Adsorption as a Function of Time for Two Different Soils.



△ One-hour Equilibration, Left and Top Scales.

⊙ 16-Hour Equilibration, Right and Bottom Scales.

Figure 11. Langmuir Isotherms for Warm Springs 37-60 in. Horizon, but with Different Equilibration Times.

ones essentially standard at this time just are not suitable for the purpose at hand in this investigation. These experimental findings would seem to further reinforce the idea that the Langmuir adsorption maximum is not a suitable criterion upon which to base phosphorus disposal capacity of a soil.

Computer program

The computer program, as discussed in the Procedure, was developed to be used in conjunction with repeated adsorption data whenever information is desired as to the maximum P disposal capacity that could be expected from a given soil area. It might also find use over a general soil area in which general agreement was found between repeated adsorption data and column behavior. In this case it would be very useful and much faster than column testing to determine the differences in P retention capacity of soils for ground water protection resulting from varying the initial conditions in either the soils or the effluent applications. Here the user should be cautioned that the values given would probably not be minimum retention capacities, but useful only as indicators of the minimum capacities upon varying the initial conditions. The computer program, along with an example showing input and output, can be found in Appendix D and E.

Relation between phosphorus retention and soil characteristics

Results of correlation analyses of the data from Table 3 are shown in Tables 4 through 6. When each soil horizon in Table 3 was

Table 4. Correlation Coefficients Between P Adsorption Maximum (Langmuir) and Various Soil Characteristics. All Soil Horizons Included (N = 20).

x	r
x_1 Percent Clay	.64**
x_2 Surface Area	.62**
x_3 CEC	.52*
x_4 $NaHCO_3$ - Soluble P	.39
x_5 Percent Organic Matter	.18
x_6 Percent $CaCO_3$	.12
$y = f(x_1) + f(x_2) + \ldots + f(x_6)$	.90
$y = f(x_2) + f(x_4) + f(x_6)$	.88
$y = f(x_2) + f(x_4)$	.79

* Significant at 5% level
** Significant at 1% level

Table 5. Correlation Coefficients Between P Adsorption and Various Soil Characteristics, Using Weighted Average Values for Each Soil (N = 5).

x	y = Adsorption Max. (Langmuir) r	y = Adsorption to .5 mg/l P (Column Tests) r
Percent Clay	.92*	.64
Surface Area	.74	.85
Percent $CaCO_3$	.65	.06
CEC	.55	.93*
$NaHCO_3$-Soluble P	.09	-.11
Percent Organic Matter	-.04	.71
Adsorption Max. (Langmuir)	--	.66

* Significant at 5% level

Table 6. Correlation Coefficients Between P Adsorption Maximum (Langmuir) and Various Soil Characteristics. Horizons Within Each Soil Considered.

x	Nibley (N=5) r	Parleys (N=5) r	Draper (N=4) r	Kilburn (N=3) r	Warm Springs (N=3) r
$NaHCO_3$-Soluble P	.99**	.98**	.90	.89	.47
Percent Organic Matter	.84	.97**	.41	.73	.72
CEC	.52	.66	.94	.78	.95
Surface Area	.41	.12	.94	.90	.99
Percent Clay	-.73	-.38	.98*	.78	.97
Percent $CaCO_3$	-.53	-.85	--	--	-.08

* Significant at 5% level
** Significant at 1% level

considered as a separate sample, the Langmuir P adsorption maximum was shown to be significantly correlated linearly with three soil properties--percent clay, surface area, and cation exchange capacity (see Table 4). These three properties were even more interrelated with each other, with an r value of 0.92 between CEC and surface area and 0.76 between percent clay and surface area. A multiple regression analysis showed that considerable improvement in explaining the variation in the adsorption maximum was gained by including all six soil properties in the model. In this case the r value was 0.90. Different properties were then successively deleted from the model to see if a fairly high r could still be obtained when including less information. After percent clay, CEC, and percent organic matter had been deleted, leaving only surface area, $NaHCO_3$-soluble P, and percent $CaCO_3$ in the model, the r value was still 0.88. The large amount of overlap among surface area, CEC, percent clay, and organic matter (r for CEC vs organic matter = 0 64) enabled the latter three properties to be dropped from the model without too much loss in the r When the model was reduced further to include only surface area and $NaHCO_3$-soluble P, the r dropped to 0.79.

Had time permitted, it would have been ideal to run soil columns with intermittent applications of different P concentrations for every horizon listed in Table 3, and then do a similar statistical analysis for the phosphorus retention capacities obtained. This procedure seemed

prohibitive, however, so the horizons were lumped into composite columns representing separate soil profiles, and were dosed continuously with only one concentration. Weighted average values of soil properties for whole soil profiles were then used for the correlation analyses as shown in Table 5. The main problem with this type of analysis is that it drastically reduces the number of experimental points from which the regression lines are computed. It is interesting to note, however, that the observed phosphorus retention capacity does not agree with the weighted average (profile) values of the Langmuir adsorption maximums. The r value between the two y values is only 0.66 (not significant) and the only properties significantly affecting either of the y values are different. This gives further evidence that the Langmuir P adsorption maximum is probably not a valid indicator of the soil's actual P retention capacity.

Finally, as shown in Table 6, Langmuir P adsorption maximums for each horizon within a soil were regressed against the corresponding soil characteristics. This shows that the P adsorption maximum may correlate with a different property, depending upon the soil considered. This is not hard to imagine, however, when considering the extreme differences found in natural soils. Again this same analysis would have been interesting had a column-derived P retention capacity been available for every soil horizon.

SUMMARY AND CONCLUSIONS

The objectives of this study were to determine the phosphate content of the ground waters of the Great Basin area of Utah, to determine the phosphorus fixing capacity of some major Great Basin soils as a basis for treatment design and/or ground water protection, and to develop a procedure for determining the potential "phosphorus disposal capacity" of soils to be used for removal of phosphorus from polluted waters.

A review of published and unpublished data and personal communication with U. S. Geological Survey and Utah State Division of Health personnel revealed that comparatively little reliable data exists on the orthophosphate content of these ground waters. However, these sources in addition to a cooperatively conducted program of well sampling and analyses resulted in the collection of data on 874 samples. These were widely scattered throughout the study area. From these data, and some rough calculations based on solubility equilibrium, it was possible to establish an approximate level of orthophosphate concentrations which might be expected to exist in average ground waters of the Great Basin area of Utah. It appeared that a close approximation to apparently unpolluted or natural phosphate concentrations could be made by assuming a solubility equilibrium with hydroxyapatite, and hence that any concentration of phosphate above about 0.2 mg/l P would probably indicate either sample contamination or actual pollution of the ground water had

occurred. This information could prove useful in the future for detecting pollution or setting quality standards in the area. There was enough data to indicate at least four local areas relatively high in phosphate content. In the future, studies should be made to determine the reason for the high values found. Some extremely high values of phosphate were questioned which might otherwise have gone unnoticed, and it is hoped there will be eventual follow-up to determine if actual ground water pollution or just sample contamination has occurred. The greatest contribution of all from this section of the study may turn out to be just the arousing of interest toward the importance of having an accurate measure of the phosphate content of the ground water.

Five Great Basin soils were selected for study and "P retention capacities" were measured. The capacities determined covered a range in values, from 76 to 319 pounds P per acre-foot of soil profile. This indicates there are great differences in the soils and it would be worthwhile to investigate thoroughly before choosing a land site for P disposal. It was pointed out that these capacities probably represent minimum values because they were derived from soil columns without vegetative cover and under continuous submergence. Data from columns as designed in this study are probably a good measure of the P removal from water if an effluent is disposed of over a soil area without any special care being taken as to the method of application. The test can be used to determine the potential hazard of ground water pollution for any given phosphate concentration of the water.

The repeated adsorption test which was developed probably represents a measure of the maximum P disposal capacity of any soil when special care is taken with the intermittent application of the effluent so that full advantage can be taken of phosphate precipitation in addition to adsorption in the soil. A computer program was presented which, when given repeated adsorption data, computes the disposal capacity of the soil given any changes in initial conditions of the soil or of the effluent applied, and subject to the limiting P concentration desired in the outflow. The program also contains a convergence check which is used essentially to sense those soils in which extensive precipitation occurs.

In the course of this dissertation the Langmuir adsorption maximum approach was discussed along with its shortcomings. Some experimental data were presented which illustrated some of the difficulties encountered. Regression analyses utilizing the data acquired for the five soils of this study also imply that the Langmuir P adsorption maximum is not a valid indicator of a soil's actual P retention capacity.

The regressions in conjunction with the Langmuir maximums do imply that it is impossible to make absolute blanket statements regarding correlation of any certain soil property with the soil's P retention capacity. They show that most of the variability in the Langmuir adsorption maximum for a soil can be explained by including several of the properties, such as surface area, $NaHCO_3$-soluble P, and percent $CaCO_3$ in the model. It is believed that somewhat similar findings would be evident

if P retention capacities from soil columns would have been available for all soil horizons and a regression were run on that data.

It is felt that from the combined results of the repeated adsorption tests, the column tests, and the regression analyses some general conclusions can be drawn. It appears that the surface area of a soil and the related properties, percent clay and cation exchange capacity, influence the P retention capacity, and are probably correlated with adsorption. It appears the amount of lime likely influences adsorption and precipitation of phosphorus. The phosphate concentration of the water and the method of application greatly affect P fixation. Therefore, the data from the column tests will show the potential ground water pollution hazard caused by indiscriminate continuous dumping of phosphorus on a high lime, low surface area soil such as Warm Springs, whereas the repeated adsorption test suggests that if care is taken with intermittent applications, the Warm Springs could potentially be a good soil for P disposal, presumably because of its phosphate precipitation capability.

Suggested Further Research

There appears to be ample opportunity for further research in areas directly related to this study. Assembling more data and performing more solubility theory calculations in some ground water basins with markedly different geology would be of great interest and benefit for detecting phosphorus pollution in the future. There should turn out to be some very good general correlations between the geology and how

much orthophosphate is expected to exist in the ground water. From this study, for example, it appeared that average Great Basin (Utah) ground water phosphate might be governed by the solubility of hydroxyapatite.

Further study should be made with soil columns. Intermittent application of phosphorus-laden water to the column should drastically increase the "P retention capacity" so obtained. In fact, this would more nearly simulate the conditions of the repeated adsorption test, and should produce better agreement between the two tests. Almost unlimited possibilities exist in checking the effects of different compositions of the applied liquid.

Both the column and the repeated adsorption methods could be evaluated by using them on the soils of an area where effluent disposals have been made, and determining how closely the test results would predict the fixation that actually occurred in the field situation. Any of the areas discussed in the "Previous Studies of Land Application" section of the Review of Literature would be suitable for this type of evaluation.

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APPENDIXES

Appendix A

Ground Water Phosphate Data

Table 7. Phosphate in Ground Water from Skull, Sink, Rush, Government Creek and Dugway Valleys. (after Waddell, 1967).

USGS Location No.	Collection Date	PO_4 (ppm)
Sink Valley Area		
(B-1-10)21dd-1	1-13-66	.16
(B-2-8)28dcb-1	4-22-64	.47
(B-3-10)29dd-1	1-13-66	.86
Skull Valley Drainage Basin		
(B-1-9)24cdd-1	12-29-65	.00
(C-1-7)31daa-1	9-5-63	.02
(C-3-7)29bcb	7-31-63	.02
(C-3-7)30ddb	7-31-63	.00
(C-3-8)25dbd	7-31-63	.02
(C-5-10)15dcc	9-5-63	.00
(C-6-7)4aba	5-29-65	.00
(C-6-8)11dad-1	5-29-65	.01
(C-6-9)6dbb	5-29-65	.24
Rush Valley Drainage Basin		
(C-4-5)33cca-1	9-25-64	.00
(C-4-5)35cba	9-22-64	.00
(C-4-7)25dcb	9-21-64	.02
(C-5-6)32bba	5-29-65	.01
(C-6-6)1bbc	9-21-64	.01
(C-7-4)14aac-1	3-30-65	.05
(C-7-5)28bbc-1	12-22-64	.06
(C-8-5)31dbc-1	12-22-64	.01
(C-8-6)10aaa-1	3-30-65	.00
(C-9-4)35bbb	3-29-65	.00
Government Creek Valley Drainage Basin		
(C-9-7)7dac	3-30-65	.25
(C-9-7)11cc	3-30-65	.00
(C-9-7)28bc	3-30-65	.00
(C-9-8)15dbd	3-31-65	.00
(C-9-8)18adb	12-29-65	.00

Table 7. Continued

USGS Location No.	Collection Date	PO_4 (ppm)
	Dugway Valley	
(C-9-11)33ccb-1	12-29-65	.01
(C-10-7)35da	8-12-64	.00
(C-10-10)31bbb-1	3-31-65	.03
(C-10-10)31bbb-1	12-29-65	.10
(C-11-9)35	4-1-65	.02
(C-11-11)12aba-1	12-24-64	.00

Table 8. Phosphate in Ground Water - Utah State Division of Health Data (from Tabulations 1964-1970).

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
1964-2	Cache	0.00	64-437	Salt Lake	0.46
64-3	Tooele	0.16	438	Salt Lake	0.14
-5	Tooele	2.40	439	Salt Lake	0.12
-6	Tooele	0.50	447	Wash.	0.10
-11	Utah	0.22	448	Wash.	0.31
-22	Wash.	0.00	479	Box Elder	0.40
-26	Box Elder	4.10	480	Box Elder	0.52
-38	Tooele	0.20	485	Iron	0.03
58	Wash.	1.10	541	Utah	0.03
59	Salt Lake	0.48	552	Salt Lake	0.22
73	Millard	0.52	553	Salt Lake	0.26
74	Millard	0.36	576	Salt Lake	0.47
80	Salt Lake	0.00	582	Utah	0.03
123	Salt Lake	0.00	594	Iron	0.34
124	Salt Lake	0.00	596	Beaver	0.48
125	Salt Lake	0.00	597	Beaver	0.24
126	Salt Lake	0.28	598	Beaver	0.17
127	Salt Lake	0.28	599	Beaver	0.28
178	Davis	0.40	600	Beaver	0.12
185	Millard	6.20	623	Sevier	0.03
186	Millard	2.40	628	Box Elder	0.24
187	Millard	1.00	629	Box Elder	0.61
188	Millard	0.68	630	Juab	0.34
195	Davis	0.44	631	Juab	0.20
203	Salt Lake	0.00	632	Millard	0.17
210	Salt Lake	0.78	633	Sevier	0.20
247	Beaver	0.03	669	Salt Lake	0.00
249	Wash.	0.00	670	Salt Lake	1.30
250	Tooele	0.00	671	Salt Lake	0.00
297	Davis	0.41	672	Salt Lake	0.00
298	Salt Lake	0.07	673	Salt Lake	0.03
303	Wash.	0.00	674	Salt Lake	0.03
334	Salt Lake	0.10	675	Salt Lake	0.00
364	Utah	0.00	676	Salt Lake	0.10
385	Wash.	0.41	677	Salt Lake	1.40
389	Davis	0.27	678	Salt Lake	0.80
393	Millard	0.14	679	Salt Lake	0.00
422	Wash.	0.10	700	Juab	0.02

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
64-720	Millard	0.01	1965-114	Weber	0.16
721	Millard	0.00	65-115	Sevier	0.00
731	Millard	0.10	155	Box Elder	0.00
783	Beaver	0.78	174	Salt Lake	0.70
806	Juab	1.40	179	Salt Lake	0.90
807	Juab	1.50	180	Davis	0.58
855	Wash.	0.00	182	Salt Lake	0.11
856	Salt Lake	1.20	183	Millard	0.00
895	Wash.	0.00	220	Utah	0.34
951	Salt Lake	0.50	233	Iron	0.00
952	Salt Lake	0.40	234	Salt Lake	0.00
953	Wash.	0.00	257	Utah	0.50
956	Wash.	0.00	262	Salt Lake	0.30
957	Wash.	0.00	264	Sevier	0.04
958	Wash.	0.00	267	Iron	0.06
986	Tooele	0.40	268	Iron	1.10
987	Tooele	0.70	269	Iron	0.40
997	Wash.	0.00	295	Utah	0.17
1965-26	Iron	0.23	313	Salt Lake	5.30
65-27	Davis	0.23	314	Salt Lake	0.60
28	Cache	0.00	315	Salt Lake	0.30
30	Utah	8.10	316	Salt Lake	0.27
31	Davis	5.80	317	Salt Lake	0.17
34	Tooele	1.20	318	Salt Lake	0.30
35	Tooele	25.00	319	Salt Lake	0.07
68	Wash.	0.00	320	Salt Lake	0.24
69	Salt Lake	0.00	321	Salt Lake	0.00
70	Salt Lake	0.10	322	Salt Lake	0.14
71	Weber	0.00	323	Salt Lake	0.28
72	Iron	0.00	325	Salt Lake	0.13
74	Tooele	24.00	326	Salt Lake	0.80
85	Davis	0.14	328	Salt Lake	0.04
91	Cache	0.61	329	Salt Lake	0.00
98	Wash.	0.00	363	Utah	0.00
100	Juab	0.58	366	Salt Lake	0.03
102	Salt Lake	0.11	368	Salt Lake	0.05
105	Salt Lake	0.84	369	Salt Lake	0.10
113	Davis	0.00	390	Salt Lake	0.50

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
1965-391	Salt Lake	0.64	1966-107	Salt Lake	0.75
392	Salt Lake	0.11	108	Salt Lake	0.09
415	Box Elder	0.00	109	Salt Lake	0.71
437	Millard	0.20	110	Salt Lake	0.00
448	Millard	1.70	111	Salt Lake	2.70
449	Cache	0.50	112	Salt Lake	1.00
450	Iron	0.20	113	Salt Lake	0.58
451	Iron	3.60	114	Salt Lake	0.00
452	Iron	3.60	115	Salt Lake	0.00
453	Iron	0.70	116	Salt Lake	0.01
483	Salt Lake	0.05	117	Salt Lake	0.00
522	Utah	0.10	118	Salt Lake	0.00
523	Utah	1.00	119	Salt Lake	0.00
524	Utah	0.05	120	Salt Lake	0.04
537	Box Elder	0.60	121	Salt Lake	0.02
538	Utah	0.00	122	Salt Lake	0.03
541	Weber	0.00	123	Salt Lake	1.00
550	Davis	0.40	124	Salt Lake	0.50
551	Wash.	0.00	125	Salt Lake	0.30
552	Wash.	0.00	126	Salt Lake	0.30
564	Sevier	0.47	127	Salt Lake	1.40
1966-1	Tooele	0.00	128	Salt Lake	0.80
66-14	Salt Lake	16.00	138	Salt Lake	0.00
30	Wash.	0.14	139	Salt Lake	0.00
31	Wash.	2.50	166	Salt Lake	0.11
46	Weber	0.00	169	Salt Lake	0.40
55	Wash.	1.90	170	Salt Lake	0.24
56	Salt Lake	0.85	171	Salt Lake	0.63
57	Utah	0.56	172	Salt Lake	0.58
74	Sevier	1.40	173	Salt Lake	0.50
99	Salt Lake	0.24	177	Wash.	0.03
100	Salt Lake	0.58	178	Wash.	0.19
101	Salt Lake	0.68	188	Beaver	0.01
102	Salt Lake	0.00	190	Wash.	0.04
103	Salt Lake	0.78	198	Salt Lake	0.07
104	Salt Lake	0.92	199	Salt Lake	0.07
105	Salt Lake	0.00	200	Salt Lake	0.12
106	Salt Lake	0.44	201	Salt Lake	0.14

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
1966-202	Salt Lake	0.05	1966-421	Salt Lake	0.08
66-204	Salt Lake	0.22	66-424	Utah	0.17
272	Iron	0.15	425	Utah	0.07
273	Salt Lake	1.40	426	Iron	0.05
274	Millard	0.03	461	Salt Lake	0.37
275	Weber	1.00	462	Salt Lake	0.22
282	Salt Lake	0.03	493	Cache	0.20
283	Salt Lake	0.03	521	Box Elder	36.00
284	Salt Lake	0.03	525	Cache	0.17
285	Salt Lake	0.01	526	Beaver	1.80
286	Salt Lake	0.03	529	Utah	0.24
287	Salt Lake	0.10	572	Salt Lake	1.50
288	Salt Lake	0.15	573	Box Elder	0.05
290	Juab	0.02	587	Salt Lake	0.03
291	Utah	0.03	588	Salt Lake	0.08
303	Iron	0.26	589	Salt Lake	1.00
305	Salt Lake	0.93	590	Salt Lake	0.08
306	Box Elder	1.30	591	Salt Lake	0.15
318	Iron	0.03	592	Salt Lake	0.09
320	Salt Lake	0.14	597	Utah	0.25
337	Iron	0.07	599	Utah	0.14
370	Utah	0.00	600	Utah	0.14
371	Utah	0.03	601	Utah	0.07
391	Salt Lake	0.01	606	Davis	0.14
392	Salt Lake	0.05	623	Iron	0.48
393	Salt Lake	0.03	624	Iron	0.20
409	Salt Lake	0.03	649	Iron	0.47
410	Salt Lake	0.18	650	Iron	0.29
411	Salt Lake	0.24	651	Iron	1.30
412	Salt Lake	0.70	652	Iron	0.42
413	Salt Lake	0.07	660	Wash.	1.10
414	Salt Lake	0.08	661	Utah	0.10
415	Salt Lake	0.10	662	Salt Lake	1.20
416	Salt Lake	0.05	663	Salt Lake	0.07
417	Salt Lake	0.14	1967-2	Beaver	0.20
418	Salt Lake	0.32	67-14	Cache	0.22
419	Salt Lake	0.07	41	Beaver	0.44
420	Davis	0.14	59	Tooele	0.00

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
1967-65	Wash.	0.17	1967-311	Iron	1.00
81	Salt Lake	0.49	312	Salt Lake	0.40
87	Davis	0.05	318	Tooele	0.20
95	Utah	0.09	330	Box Elder	0.50
100	Salt Lake	1.15	331	Davis	0.60
101	Davis	0.05	333	Salt Lake	0.50
102	Davis	0.10	334	Salt Lake	0.50
105	Tooele	1.50	335	Salt Lake	0.50
137	Wash.	2.50	336	Salt Lake	1.20
140	Davis	0.00	337	Salt Lake	1.20
161	Weber	2.00	338	Wash.	0.90
162	Weber	1.00	339	Wash.	0.70
166	Utah	1.00	390	Davis	0.30
171	Tooele	0.40	393	Davis	0.50
192	Salt Lake	1.30	395	Iron	0.40
195	Davis	0.50	420	Tooele	1.10
214	Utah	0.00	460	Utah	0.40
215	Utah	0.00	462	Utah	0.30
216	Davis	0.80	472	Utah	0.50
217	Davis	0.50	473	Utah	1.30
235	Cache	0.80	500	Davis	0.80
253	Wash.	1.30	1968-1	Utah	0.60
257	Davis	1.30	15	Salt Lake	1.00
262	Salt Lake	0.40	16	Iron	0.90
265	Salt Lake	0.20	22	Salt Lake	0.60
266	Salt Lake	0.30	23	Tooele	2.10
267	Salt Lake	0.40	25	Utah	0.40
268	Salt Lake	0.40	28	Salt Lake	0.70
269	Salt Lake	0.40	30	Davis	0.50
270	Salt Lake	0.40	59	Salt Lake	19.00
271	Salt Lake	0.50	79	Salt Lake	1.00
272	Salt Lake	0.60	101	Weber	0.40
273	Salt Lake	0.60	102	Weber	0.40
274	Salt Lake	0.80	103	Tooele	0.30
275	Salt Lake	0.80	156	Sanpete	0.70
276	Salt Lake	0.80	173	Cache	1.40
305	Iron	1.40	183	Wash.	0.70
306	Salt Lake	0.20	184	Millard	1.30

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
194	Iron	1.00	589	Box Elder	0.10
214	Wash.	0.10	590	Utah	0.10
215	Iron	0.80	597	Wash.	0.70
226	Cache	0.20	607	Sevier	0.60
231	Wash.	1.00	608	Sevier	2.10
245	Salt Lake	0.90	611	Beaver	0.70
246	Salt Lake	1.00	651	Beaver	1.40
257	Utah	0.60	652	Iron	1.60
268	Wash.	1.00	705	Wash.	0.30
325	Salt Lake	3.00	706	Wash.	0.30
338	Salt Lake	0.40	709	Davis	0.00
363	Utah	3.00	1969-9	Tooele	2.20
364	Utah	0.50	69-10	Utah	1.70
386	Salt Lake	5.60	63	Weber	0.80
387	Salt Lake	5.40	64	Weber	0.90
388	Salt Lake	5.20	66	Weber	1.00
389	Iron	2.30	68	Weber	0.70
390	Iron	2.30	69	Weber	0.60
428	Box Elder	5.20	70	Weber	0.50
447	Salt Lake	0.20	71	Salt Lake	0.60
448	Salt Lake	1.00	72	Salt Lake	0.80
1968-449	Salt Lake	0.80	74	Salt Lake	0 90
450	Salt Lake	0.40	76	Salt Lake	1.00
451	Salt Lake	0.20	77	Salt Lake	1.00
452	Salt Lake	0.60	78	Salt Lake	1.00
453	Salt Lake	0.50	84	Wash.	1.00
454	Salt Lake	0.20	87	Davis	1.10
455	Salt Lake	0.20	89	Davis	0.90
456	Salt Lake	0.20	90	Davis	1.00
457	Salt Lake	0.20	93	Utah	0.50
469	Salt Lake	0.10	94	Utah	0.30
470	Wash.	0.40	95	Utah	0.50
471	Salt Lake	0.20	97	Utah	0.50
472	Tooele	0.10	98	Utah	0.50
504	Tooele	0.40	99	Utah	0.70
505	Weber	0.60	100	Utah	1.10
517	Wash.	0.80	101	Utah	0.30
531	Davis	0.60	102	Utah	0.70
553	Utah	1.00	103	Utah	0.30

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
106	Davis	0.70	211	Sevier	2.20
107	Davis	1.00	212	Sevier	2.00
108	Davis	1.20	215	Utah	0.60
109	Salt Lake	0.20	236	Salt Lake	0.50
110	Salt Lake	0.20	243	Box Elder	0.80
111	Salt Lake	1.00	244	Box Elder	0.20
113	Salt Lake	0.50	245	Box Elder	0.40
114	Salt Lake	1.10	246	Box Elder	0.40
115	Salt Lake	2.20	1969-248	Utah	0.50
116	Salt Lake	3.60	249	Utah	0.60
1969-117	Salt Lake	0.20	252	Utah	0.50
118	Salt Lake	2.20	255	Wash.	1.00
119	Salt Lake	0.80	268	Wash.	0.60
120	Salt Lake	1.00	269	Wash.	1.10
121	Salt Lake	1.50	270	Wash.	0.90
122	Salt Lake	2.00	271	Wash.	0.90
123	Sevier	2.00	272	Wash.	0.90
124	Sanpete	0.00	273	Weber	0.50
125	Sanpete	0.20	275	Beaver	1.00
126	Sanpete	0.00	276	Beaver	2.50
127	Sanpete	0.00	277	Beaver	1.10
128	Juab	0.20	278	Iron	1.10
139	Davis	2.50	279	Iron	0.80
140	Davis	1.00	280	Iron	0.70
141	Davis	1.00	281	Iron	0.80
142	Davis	1.00	286	Utah	0.90
143	Tooele	1.10	287	Wash.	0.70
160	Tooele	0.90	310	Wash.	1.00
161	Tooele	0.60	351	Tooele	0.90
163	Salt Lake	0.90	354	Cache	0.30
165	Millard	1.70	355	Cache	0.40
186	Davis	0.50	357	Cache	0.50
187	Millard	0.30	370	Salt Lake	1.90
188	Millard	1.20	372	Davis	5.20
189	Millard	0.50	374	Wash.	0.80
190	Sevier	0.40	375	Wash.	1.00
207	Box Elder	2.60	377	Salt Lake	1.80
208	Weber	0.20	378	Salt Lake	1.40
209	Salt Lake	0.50	379	Salt Lake	1.20
210	Sevier	2.00	380	Utah	2.20

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
381	Utah	2.20	533	Millard	0.50
382	Utah	1.80	534	Sanpete	1.60
383	Utah	1.70	535	Sanpete	2.20
384	Utah	2.20	536	Salt Lake	1.50
385	Utah	1.90	537	Salt Lake	1.70
386	Weber	0.60	538	Millard	1.00
1969-391	Salt Lake	0.90	559	Box Elder	1.60
393	Davis	0.40	560	Box Elder	1.00
394	Davis	0.90	567	Box Elder	0.60
395	Davis	0.70	575	Iron	1.70
396	Davis	0.70	580	Salt Lake	0.80
416	Salt Lake	0.60	581	Salt Lake	0.60
419	Beaver	1.50	582	Wash.	1.80
420	Beaver	1.60	625	Tooele	1.20
421	Beaver	1.20	635	Salt Lake	0.90
429	Beaver	1.30	646	Iron	0.60
430	Beaver	1.90	647	Wash.	1.30
431	Tooele	0.80	655	Tooele	0.60
432	Tooele	1.00	656	Utah	1.50
433	Tooele	0.60	678	Utah	0.60
443	Wash.	0.80	679	Utah	1.30
448	Iron	1.00	728	Wash.	0.50
479	Sevier	1.00	754	Utah	0.10
480	Sevier	0.90	755	Utah	0.10
482	Sevier	0.90	758	Davis	0.20
483	Millard	1.00	1970-33	Beaver	0.20
484	Sanpete	0.50	1970-34	Beaver	0.40
499	Salt Lake	1.30	45	Utah	0.20
501	Salt Lake	0.60	55	Tooele	0.20
502	Salt Lake	0.80	63	Weber	0.00
503	Salt Lake	0.80	86	Sevier	0.30
504	Salt Lake	1.60	89	Tooele	0.00
505	Salt Lake	0.70	101	Box Elder	0.10
506	Cache	0.50	113	Utah	0.00
527	Iron	1.50	114	Utah	0.10
528	Iron	1.00	155	Utah	0.00
529	Iron	1.50	171	Utah	8.80
530	Iron	1.30	192	Box Elder	0.10
531	Iron	0.50	193	Box Elder	0.00

Table 8. Continued

Div. Health Lab. No.	County	PO_4 (ppm)	Div. Health Lab. No.	County	PO_4 (ppm)
1970-194	Box Elder	0.00	422	Salt Lake	0.00
195	Box Elder	0.30	423	Salt Lake	0.00
221	Tooele	0.00	424	Salt Lake	0.00
222	Salt Lake	0.00	425	Salt Lake	0.00
223	Weber	1.10	426	Salt Lake	0.00
224	Weber	0.10	427	Salt Lake	0.00
246	Cache	0.20	428	Salt Lake	0.00
276	Utah	0.10	455	Iron	0.10
291	Salt Lake	0.30	459	Cache	0.00
311	Wash.	0.20	460	Box Elder	0.00
315	Beaver	0.30	461	Box Elder	0.40
316	Millard	0.20	464	Wash.	0.10
332	Utah	0 20	465	Utah	0.20
333	Utah	0.20	471	Salt Lake	0.20
334	Utah	0.10	486	Utah	0.10
335	Salt Lake	0.20	487	Utah	0.10
336	Utah	0.20	506	Cache	0.10
337	Utah	0.50	507	Davis	0.90
338	Weber	0.00	537	Salt Lake	0.10
340	Wash.	0.00	544	Davis	0.30
354	Salt Lake	0.00	550	Salt Lake	0.10
358	Tooele	0.20	570	Salt Lake	0.10
359	Salt Lake	0.20	572	Utah	0.00
361	Salt Lake	0.20	577	Sevier	0.10
362	Salt Lake	0.80	587	Salt Lake	0.10
363	Utah	0.20	591	Wash.	0.10
370	Utah	0.00	599	Juab	0.10
375	Davis	0.50	600	Juab	0.10
380	Weber	0.20	607	Weber	0.10
399	Box Elder	0.20	618	Salt Lake	0.10
400	Juab	0.10	619	Millard	1.60
401	Tooele	0.10	647	Wash.	0.00
415	Salt Lake	0.20	648	Wash.	0.00
416	Salt Lake	0.20	652	Davis	0.90
417	Salt Lake	0.10	653	Cache	0.00
418	Salt Lake	0.00			
419	Salt Lake	0.00			
420	Salt Lake	0.00			
421	Salt Lake	0.00			

Table 9. Phosphate in Ground Water - Samples Collected in Great Basin Area of Utah Cooperatively by USGS for this Study.

USGS Location No.	Collection Date	PO_4 (ppm)
(A-11-1)8dda-3	5-26-69	.01
(B-2-1) 27ddd-4	10-1-69	.06
(B-2-1)35dbd-1	10-1-69	.09
(B-3-1)25dab-1	10-1-69	.04
(B-4-2)6baa-1	10-1-69	.06
(B-4-2)17cdd-1	10-1-69	.09
(B-4-2)20ada-1	10-1-69	.15
(B-4-2)27aba-1	10-1-69	1.95
(B-5-3)15dda-1	10-2-69	.20
(B-6-2)1baa-3	10-3-69	.07
(B-6-2)5acb-2	10-3-69	.20
(B-6-2)20cdd-1	10-2-69	.17
(B-6-3)17cca-1	10-3-69	.14
(B-6-3)26bbb-1	10-3-69	.15
(B-7-1)30dca-1	10-3-69	.05
(B-7-1)31bdb-1	10-3-69	.06
(B-7-2)21dcc-1	10-3-69	2.80
(B-7-2)23dbd-1	10-3-69	.09
(B-10-18)33aaa	7-23-69	.02
(B-11-2)8aaa-1	9-9-69	.00
(B-11-4)3ccc-1	9-9-69	.00
(B-11-18)33bdc-1	8-19-69	.06
(B-12-4)27dbd-1	9-9-69	.01
(B-12-4)34bbd-1	9-9-69	.00
(B-12-4)34cbd-1	9-9-69	.01
(B-12-11)5bbb-1	7-26-69	.01
(B-12-18)32aad-1	7-24-69	.01
(B-12-18)32aad-1	8-19-69	.01
(B-14-4)1dad-1	9-9-69	.01
(B-14-9)5bbb	7-28-69	.01
(B-14-10)1bbb	7-28-69	.01
(B-15-9)28cbb	7-28-69	.02
(C-2-1)15dda-1	8-12-69	.05
(C-2-4)22ccb-4	9-3-69	.02
(C-2-4)22ccb-4	7-12-70	.02
(C-2-5)33dad-3	7-10-69	.02
(C-3-5)4bbb-1	7-10-69	.01
(C-3-5)4bbb-1	7-11-70	.01
(C-4-5)32ddc-1	9-17-69	.02

Table 9. Continued

USGS Location No.	Collection Date	PO_4 (ppm)
(C-10-1)3ddb-1	8-5-70	.23
(C-10-1)4cbb-1	8-5-69	.02
(C-10-1)4cbb-1	8-5-70	.02
(C-12-1)24baa-1	7-28-70	.01
(C-15-4)8cba-1	8-24-69	.07
(C-15-4)8cba-1	8-28-70	.02
(C-15-4)26dcc-1	6-13-69	.02
(C-15-4)26dcc-1	7-7-70	.01
(C-15-4)26dcc-1	8-28-70	.01
(C-15-5)13bbc-1	6-9-69	.05
(C-16-8)26bdb-2	6-13-69	.13
(C-16-8)26bdb-2	7-7-70	.12
(C-18-1)25ddc-1	8-5-69	.02
(C-18-1)25ddc-1	6-26-70	.02
(C-19-4)29bcd-1	6-10-69	.00
(C-19-4)29bcd-1	7-8-70	.01
(C-19-4)31dbb-1	6-19-69	.00
(C-19-4)31dbb-1	7-8-70	.02
(C-21-1)13abd-1	9-16-69	.03
(C-21-1)13abd-1	6-26-70	.02
(C-21-5)7cdd-3	6-10-69	.01
(C-21-5)7cdd-3	7-9-70	.02
(C-21-5)8bdc-2	6-10-69	.00
(C-21-5)8bdc-2	7-9-70	.01
(C-21-5)30dbc-3	6-12-69	.01
(C-21-5)30dbc-3	7-8-70	.01
(C-23-2)15dab-4	6-26-70	.12
(C-23-2)19dab-1	7-6-70	.01
(C-23-5)5acd-1	6-12-69	.01
(C-23-6)8abd-1	7-7-70	.02
(C-23-6)9ccd-1	8-26-69	.01
(C-23-6)9ccd-1	7-7-70	.02
(C-23-6)10cdc-1	6-18-69	.01
(C-23-6)15bca-1	6-18-69	.01
(C-23-6)16bad-1	8-26-69	.06
(C-23-6)16bad-1	7-7-70	.02
(C-23-6)16cda-1	8-26-69	.09
(C-23-6)16cda-1	7-7-70	.02
(C-23-6)21add-1	7-7-70	.02

Table 9. Continued

USGS Location No.	Collection Date	PO_4 (ppm)
(C-23-6)21bdd-1	6-18-69	.01
(C-23-6)21bdd-1	7-7-70	.02
(C-24-2)6abc-1	7-14-69	.01
(C-24-2)6abc-1	6-26-70	.04
(C-26-1)23ddb-1	7-14-70	.03
(C-28-10)5dad-2	6-25-70	.17
(C-28-10)5ddd-1	6-25-70	.03
(C-28-10)17ccc-1	8-18-70	.07
(C-28-10)28cdd-1	8-26-69	.14
(C-28-10)28cdd-1	6-25-70	.01
(C-28-10)30bdd-1	8-25-69	.01
(C-28-10)3-bdd-3	6-25-70	.06
(C-28-11)23cbb-2	9-4-69	.03
(C-28-11)23cbb-2	6-25-70	.12
(C-28-11)25dcd-1	8-26-69	.01
(C-28-11)25dcd-1	6-25-70	.02
(C-29-8)25cac-2	8-25-69	.04
(C-29-8)31add-1	8-25-69	.16
(C-29-10)5ccd-3	8-26-69	.11
(C-29-10)5ccd-3	6-25-70	.09
(C-29-10)18add-2	8-26-69	.09
(C-29-10)18add-2	6-25-70	.07
(C-29-10)28add-2	6-25-70	.07
(C-29-11)1add-2	8-26-69	.10
(C-29-11)1add-2	6-25-70	.08
(C-29-11)11cdd-2	7-29-69	.00
(C-31-2)23bcd-1	7-7-70	.15
(C-32-5)35bab-1	9-13-69	.04
(C-32-5)35bab-1	3-9-70	.01
(C-33-8)31ccc-2	8-26-69	.04
(C-33-9)35acd-2	8-26-69	.02
(C-34-9)16cdd-2	9-11-69	.08
(C-34-10)13cbd-2	8-27-69	.03
(C-34-16)28ddc-2	7-22-70	.02
(C-35-9)35acd-2	7-1-70	.01
(C-35-16)9add-1	7-22-70	.03
(C-35-16)32dcd-1	8-27-69	.07
(C-36-11)18ada-1	9-10-69	.06
(C-36-11)18ada-1	6-25-70	.02
(C-36-12)12dba-1	9-10-69	.02

Table 9. Continued

USGS Location No.	Collection Date	PO_4 (ppm)
(C-36-12)20acc-1	6-3-69	.03
(C-36-12)32dbb-1	8-15-70	.41
(C-36-15)7dcc-1	7-22-70	.16
(C-36-16)5a-9	8-27-69	.15
(C-36-16)6b-1	9-4-69	.03
(C-36-16)9bcd-1	7-22-70	.05
(C-36-16)19abb-1	8-27-69	.12
(C-36-16)19abb-1	7-22-70	.03
(C-36-16)27dcc-1	8-27-69	.07
(C-36-16)27dcc-1	8-18-70	.08
(C-36-16)31ccc-1	7-22-70	.09
(C-37-12)15cdc-1	10-7-69	.02
(C-37-12)23aca	9-10-69	.04
(C-37-12)34abb-1	8-29-69	.01
(C-37-17)12bdc-1	7-22-70	.02
(C-37-17)14bac-1	8-18-70	.06
(C-43-15)12ccd-1	6-2-69	.00
(D-5-1)18cab-2	8-29-69	.04
(D-5-1)19ccc-1	8-29-69	.02
(D-5-2)30cbd-1	9-4-69	.01
(D-7-3)28bdb-1	9-3-69	.01
(D-8-2)12ddc-1	9-3-69	.14
(D-8-2)12ddc-1	8-5-70	.07
(D-8-2)12ddc-2	9-3-69	.06
(D-8-2)12ddc-2	8-5-70	.04
(D-8-2)23dca-2	7-30-70	.03
(D-9-1)36bbc-1	9-3-69	.00
(D-9-2)9bac-1	7-30-70	.02
(D-9-3)5bbd-1	9-3-69	.01
(D-12-1)19dbb-1	9-11-69	.05
(D-13-1)5ddb-2	7-28-70	.01
(D-13-1)7dbc-1	7-28-70	.01

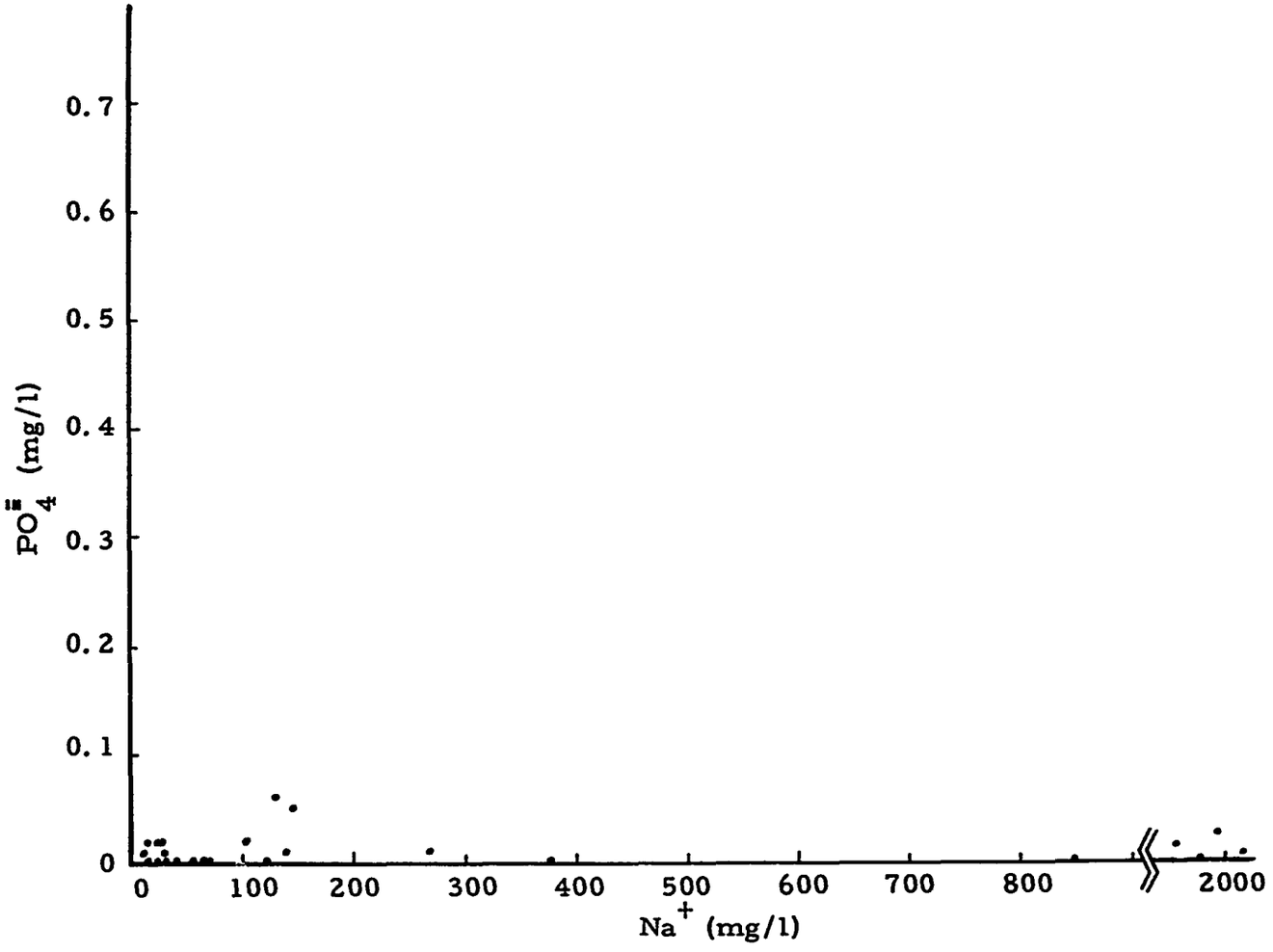


Figure 12. Dissolved Orthophosphate in Ground Water as Related to Sodium Content. (Data from Waddell, 1967).

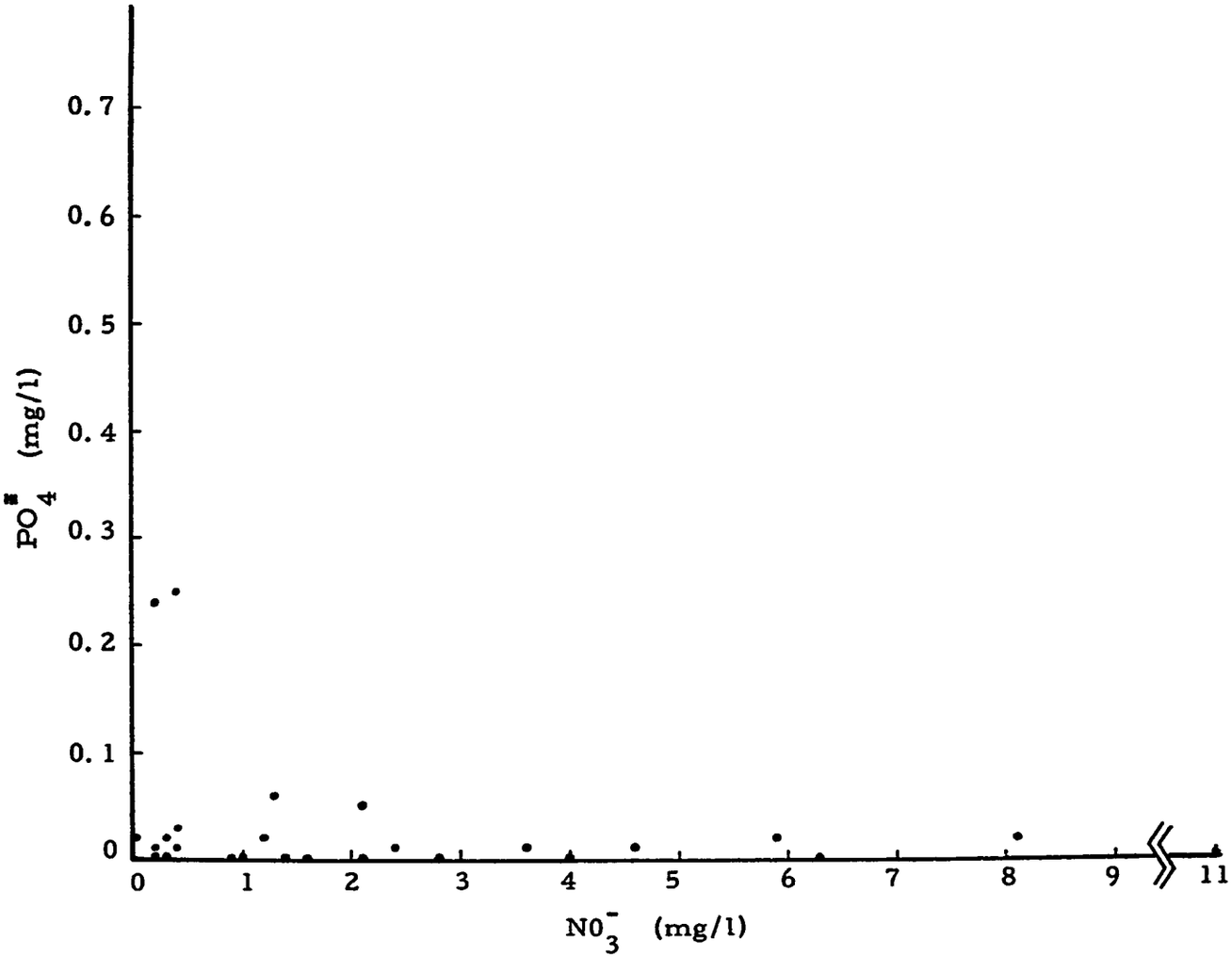


Figure 13. Dissolved Orthophosphate in Ground Water as Related to Nitrate Content. (Data from Waddell, 1967).

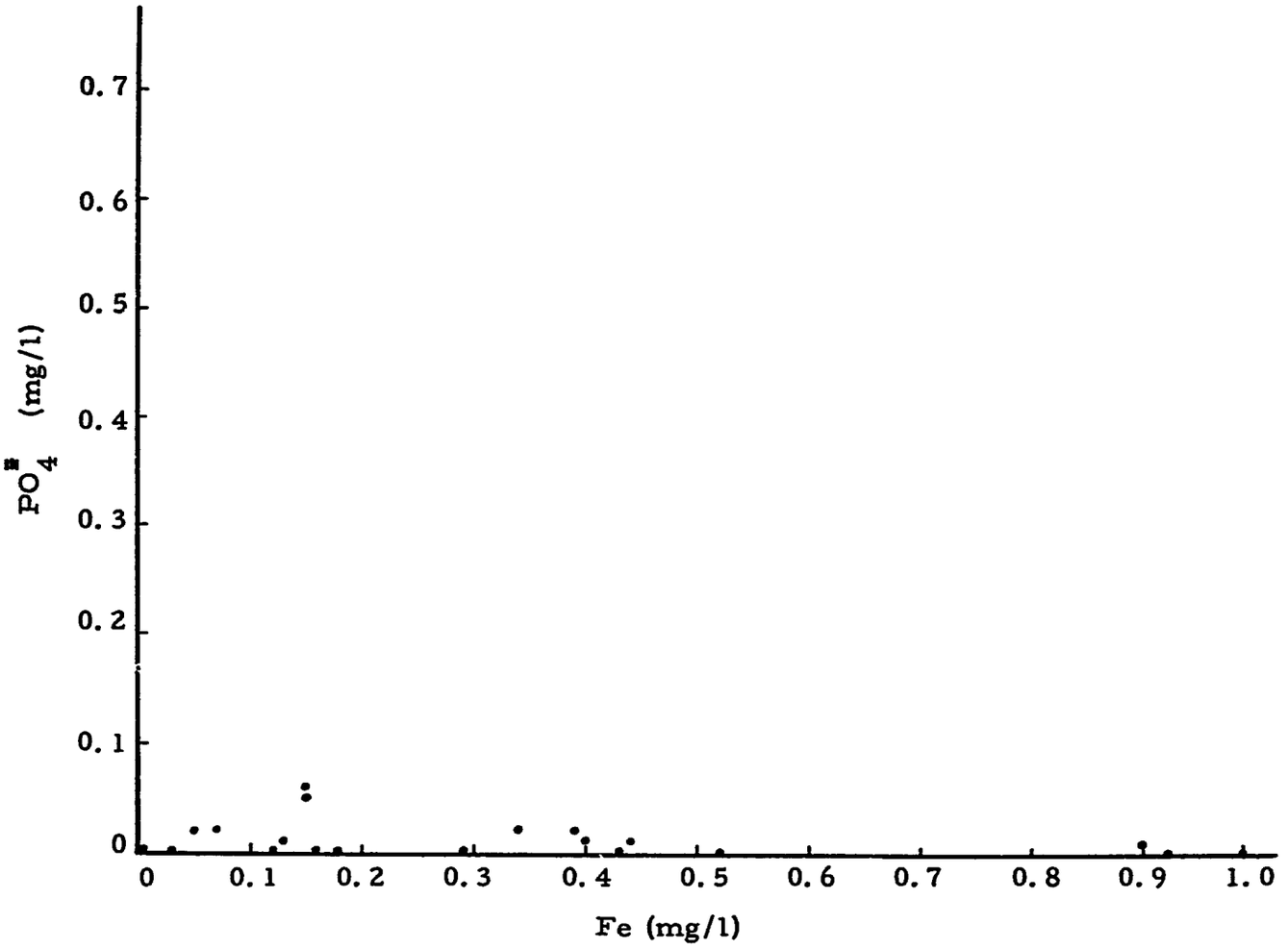


Figure 14. Dissolved Orthophosphate in Ground Water as Related to Iron Content. (Data from Waddell, 1967).

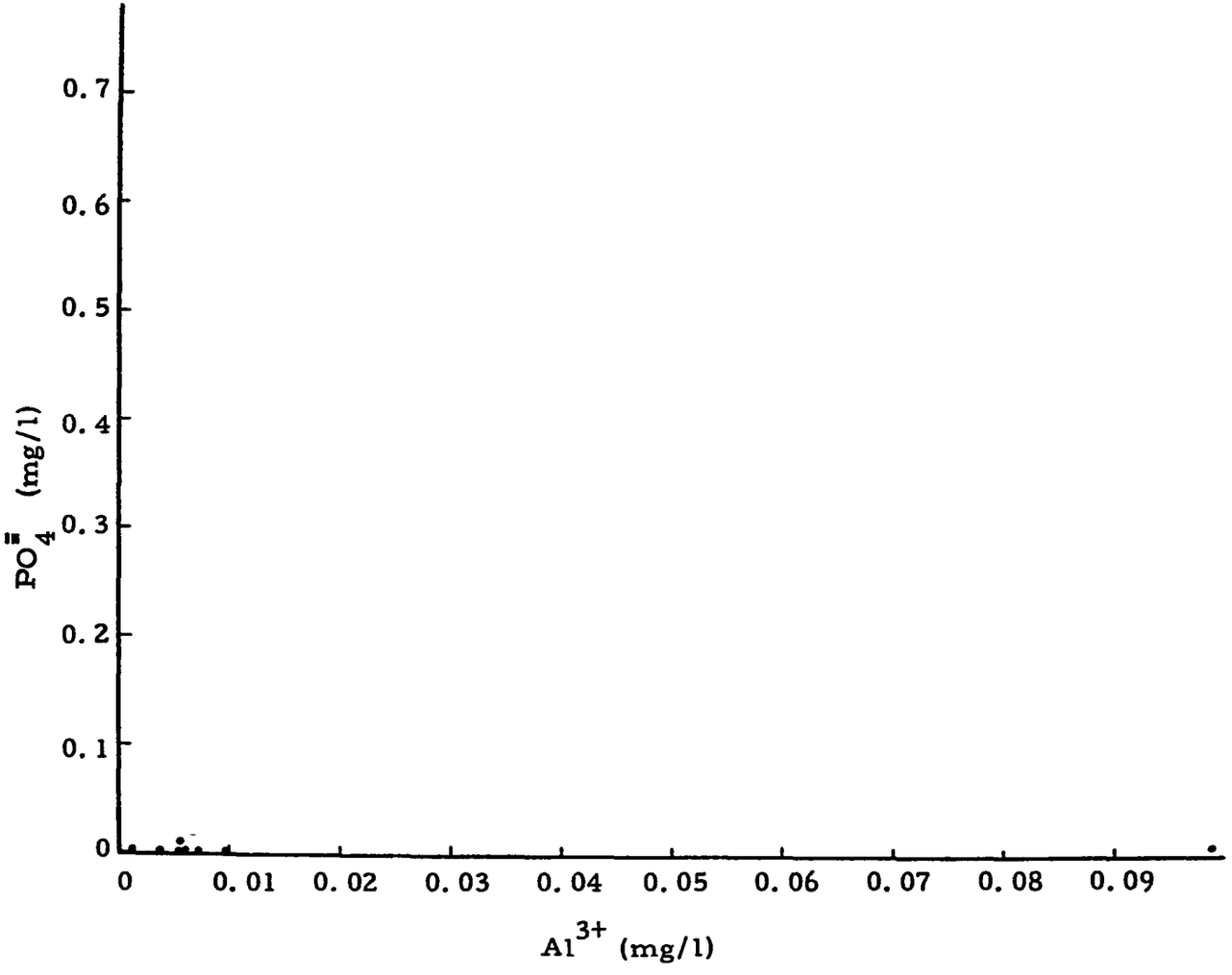


Figure 15. Dissolved Orthophosphate in Ground Water as Related to Aluminum Content. (Data from Waddell, 1967).

Appendix B

Soil Column Breakthrough Curves

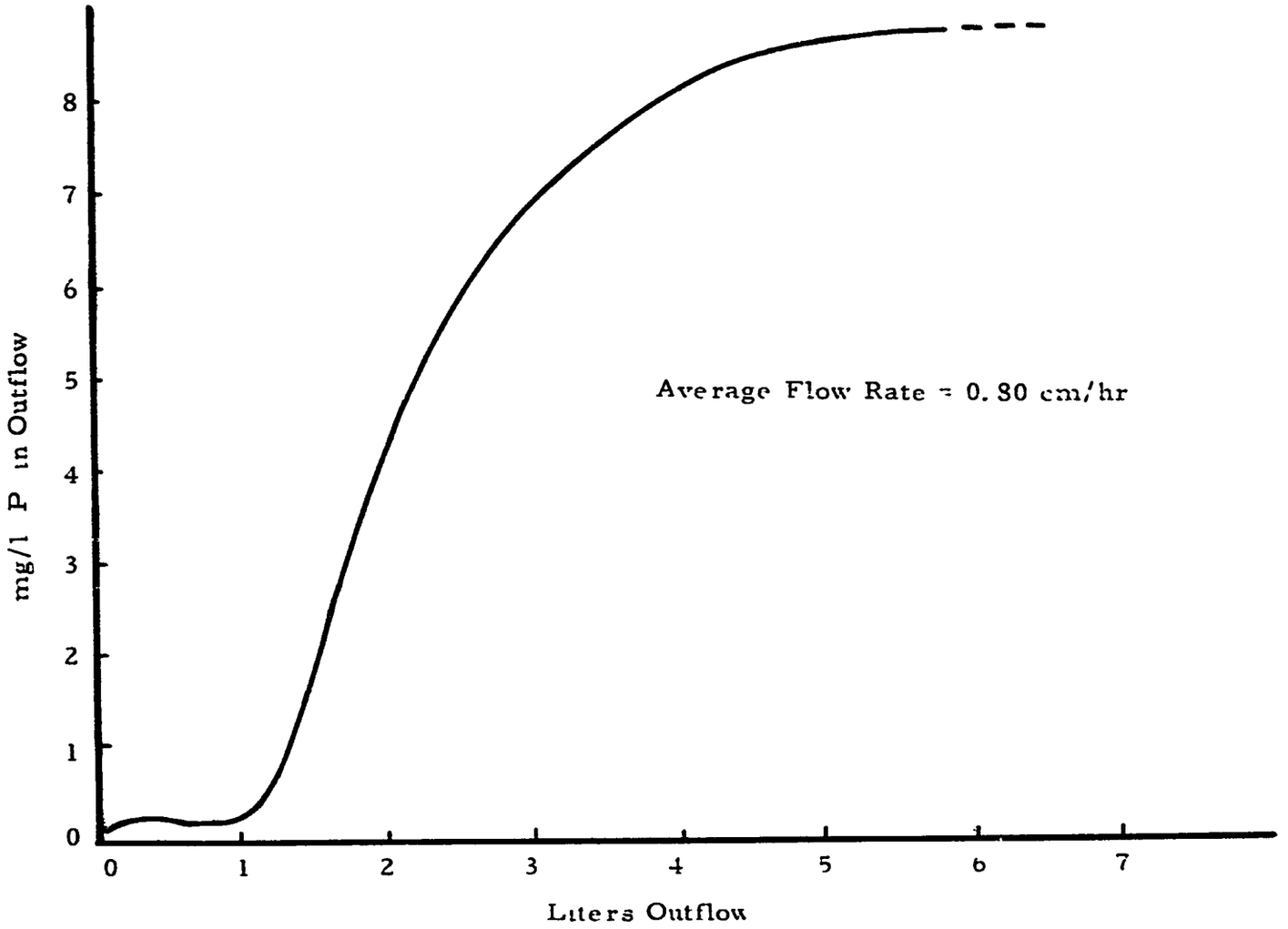


Figure 16. Phosphorus Breakthrough Curve from Soil Column Test 2. Warm Springs Soil Profile

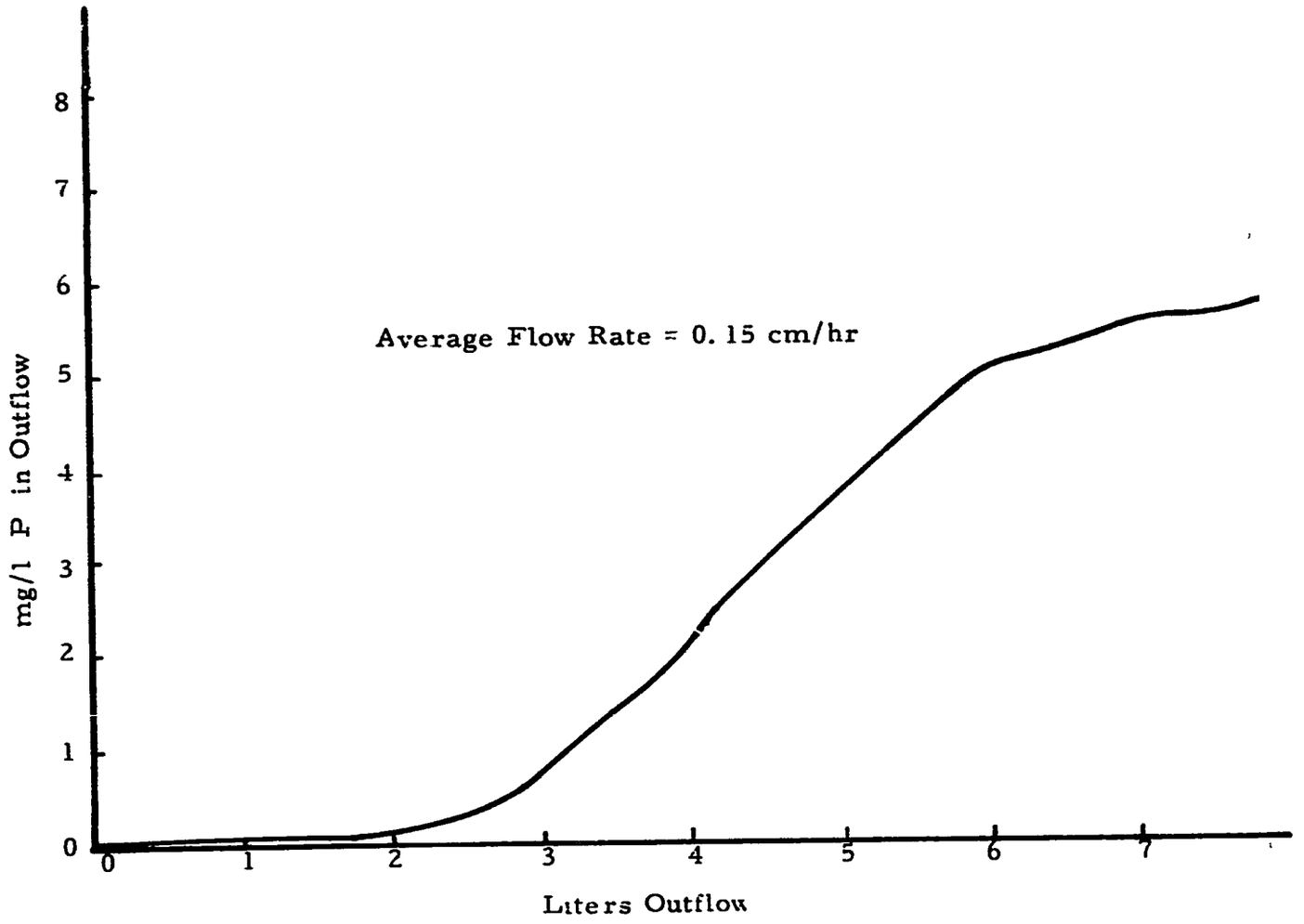


Figure 17. Phosphorus Breakthrough Curve from Soil Column Test 4. Kilburn Soil Profile.

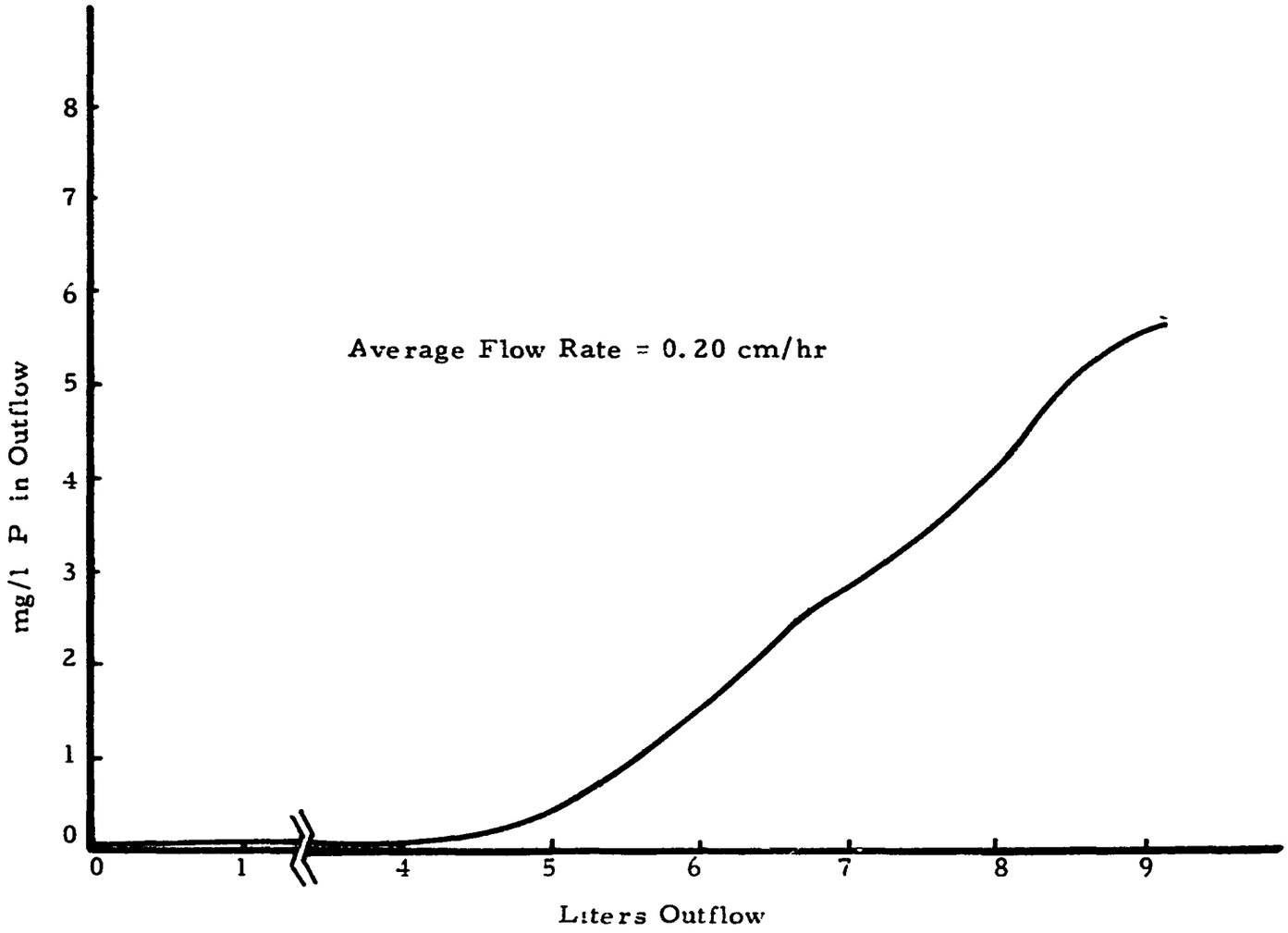


Figure 18. Phosphorus Breakthrough Curve from Soil Column Test 5. Nibley Soil Profile

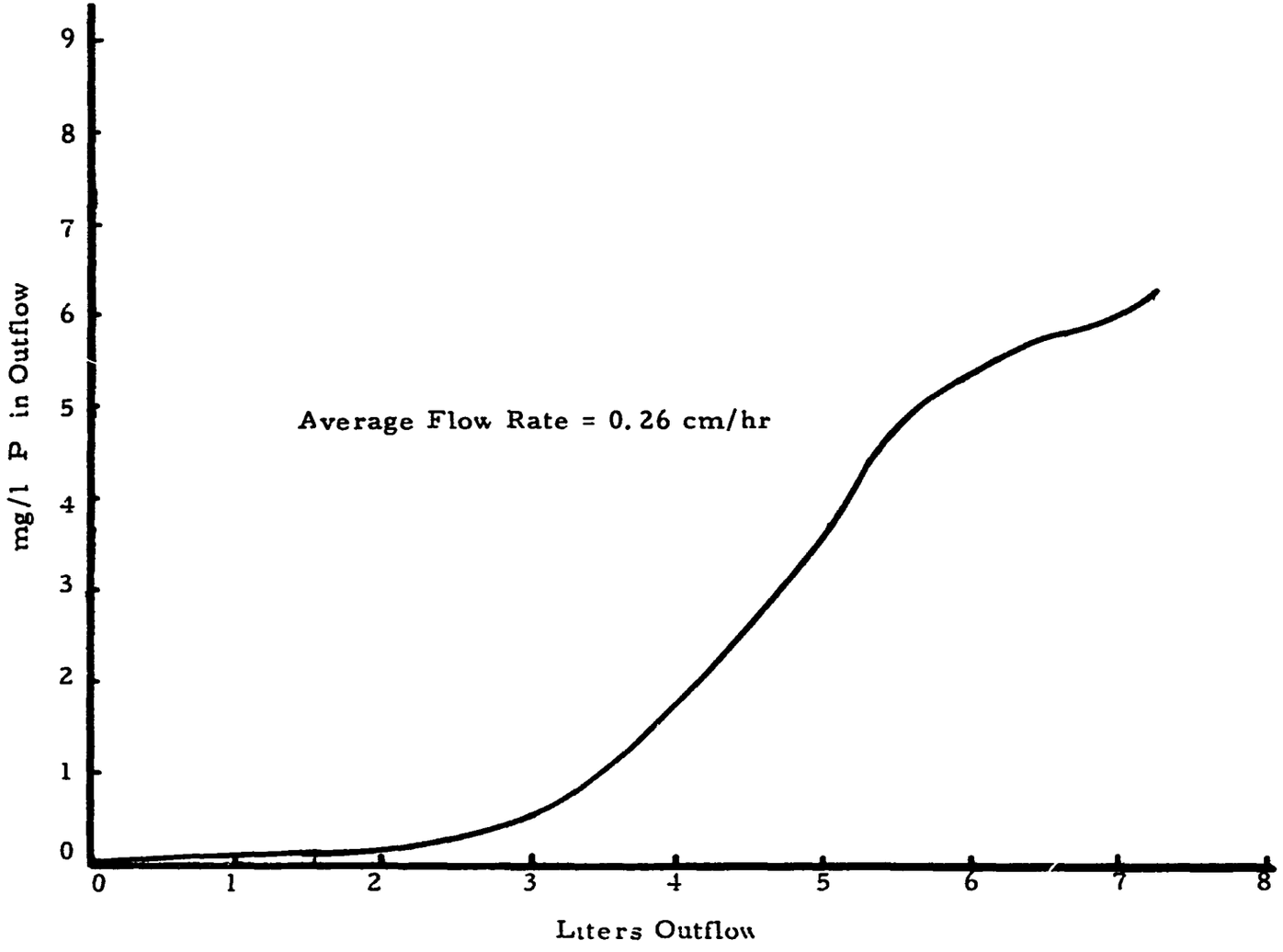


Figure 19 Phosphorus Breakthrough Curve from Soil Column Test 10, Nibley 0-7 in. Horizon.

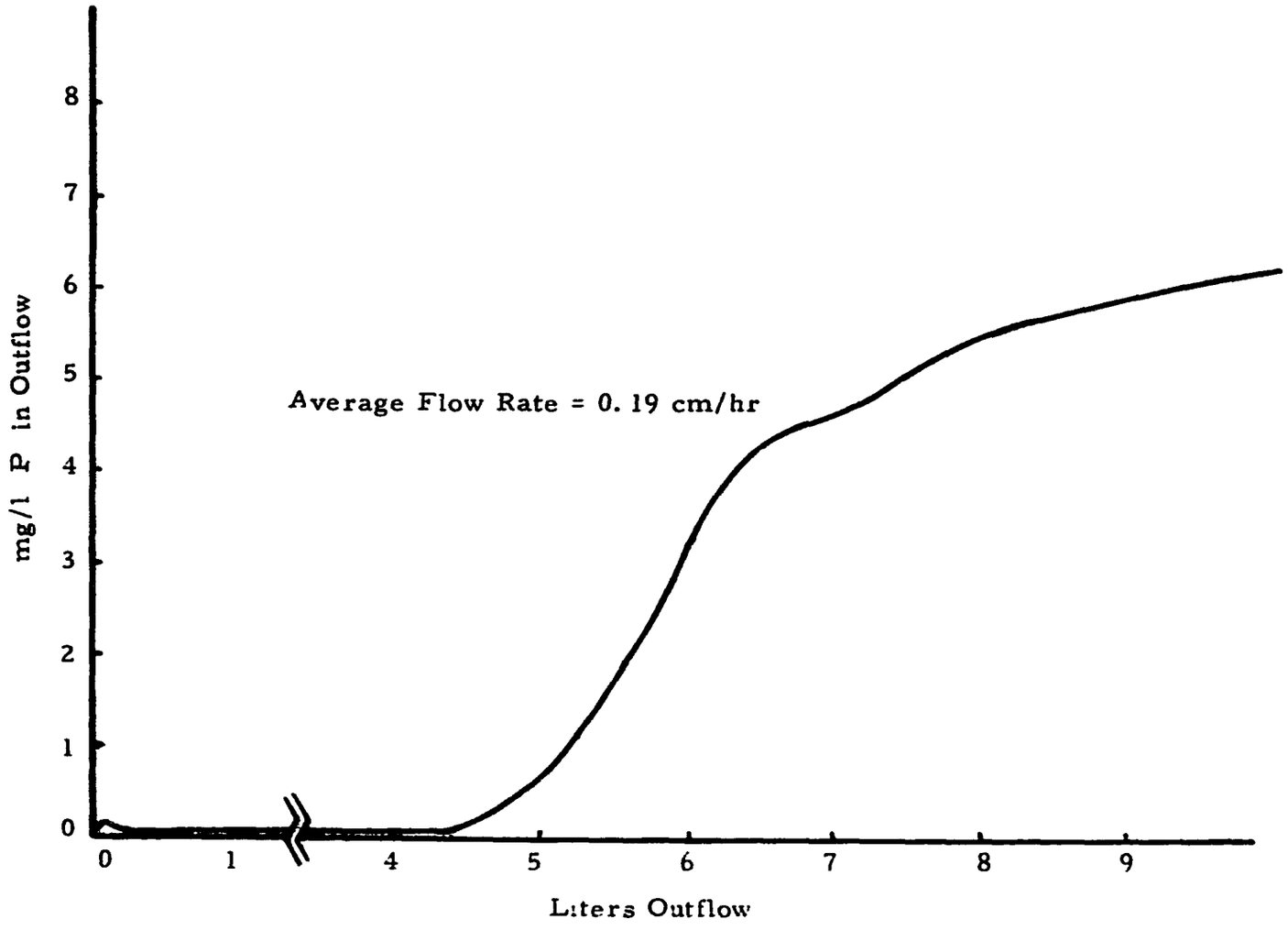


Figure 20. Phosphorus Breakthrough Curve from Soil Column Test 3. Parleys Soil Profile.

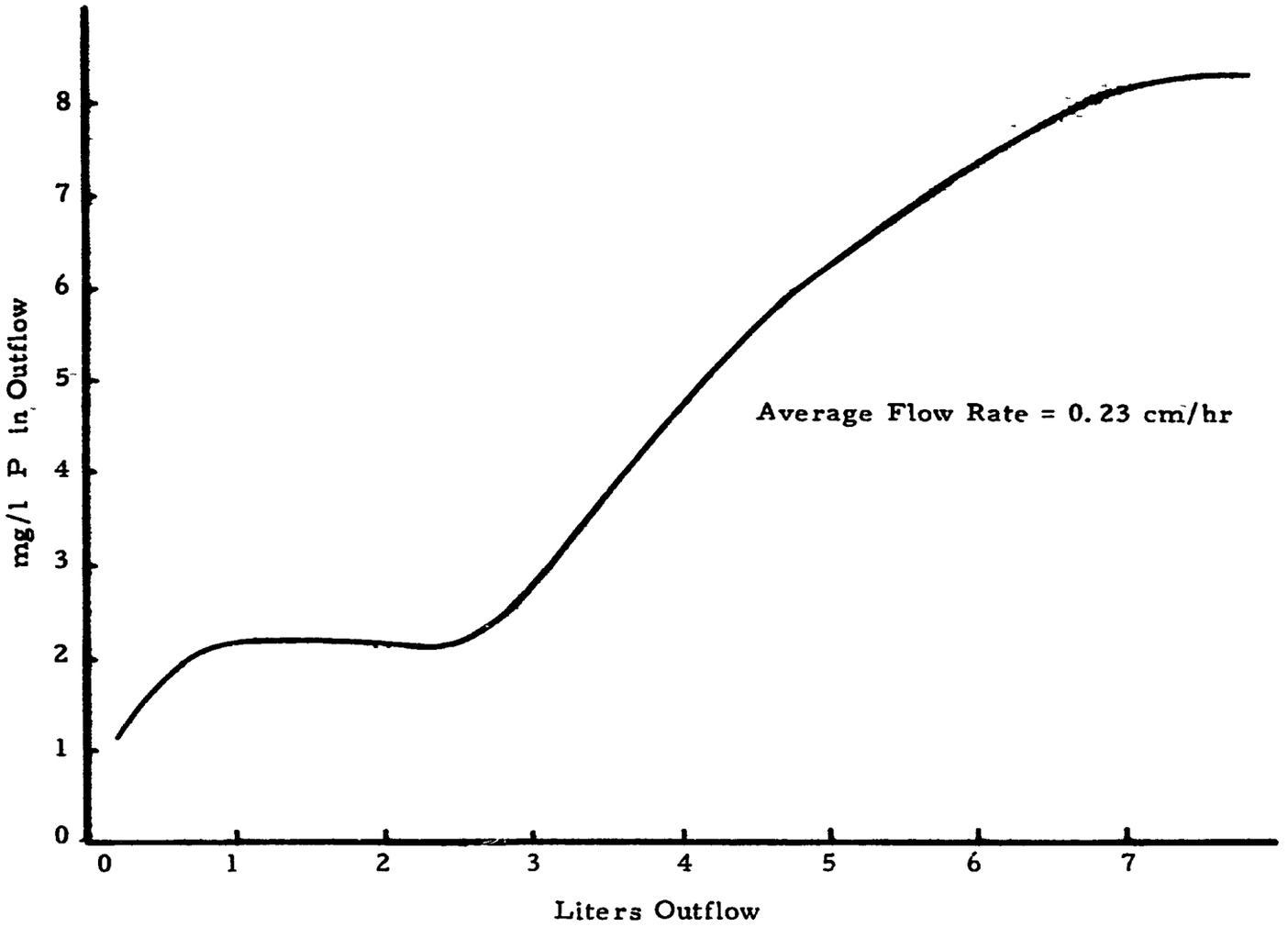


Figure 21. Phosphorus Breakthrough Curve from Soil Column Test 8, Parleys 6-15 in Horizon.

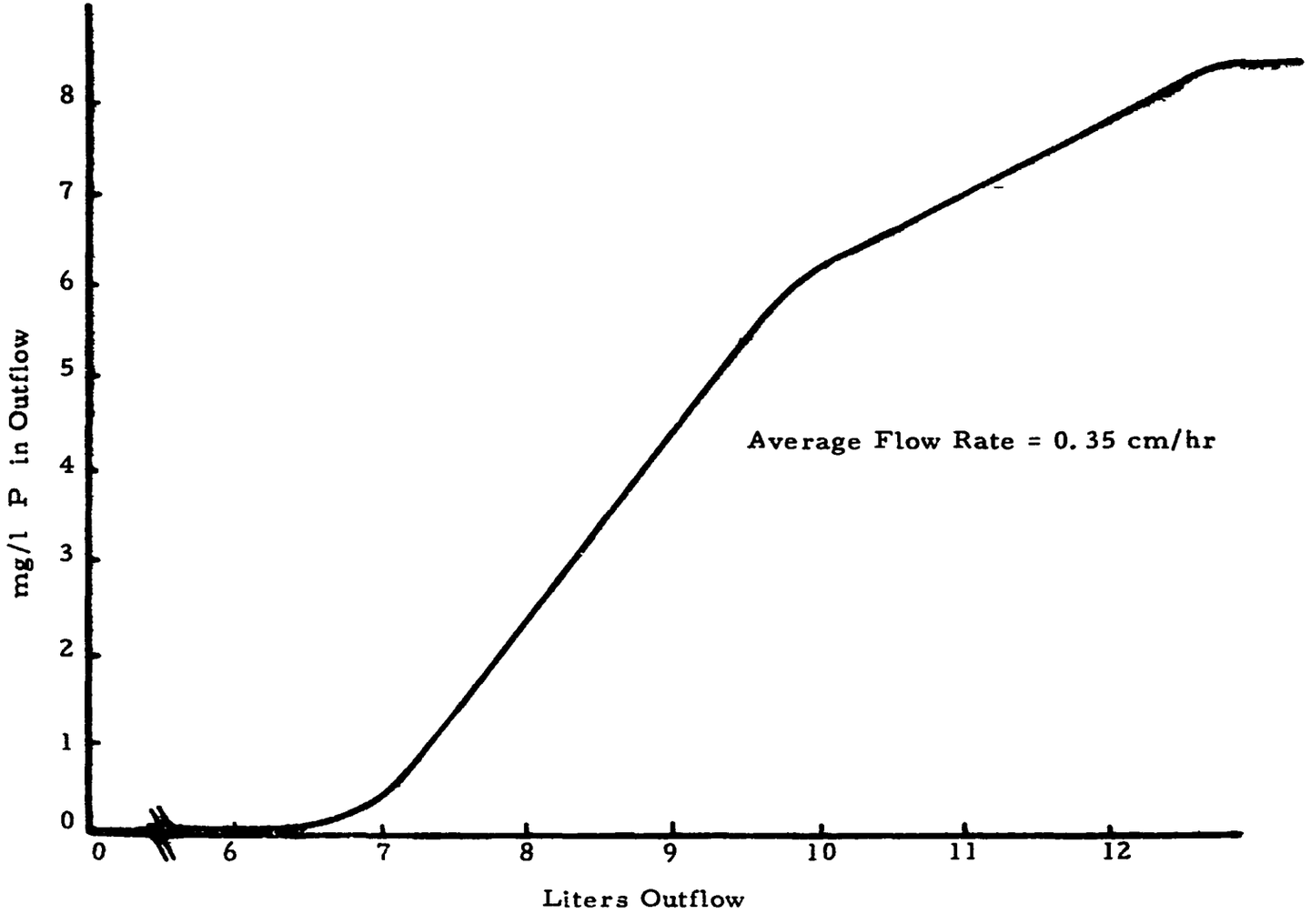


Figure 22. Phosphorus Breakthrough Curve from Soil Column Test 9, Parleys 26-33 in. Horizon.

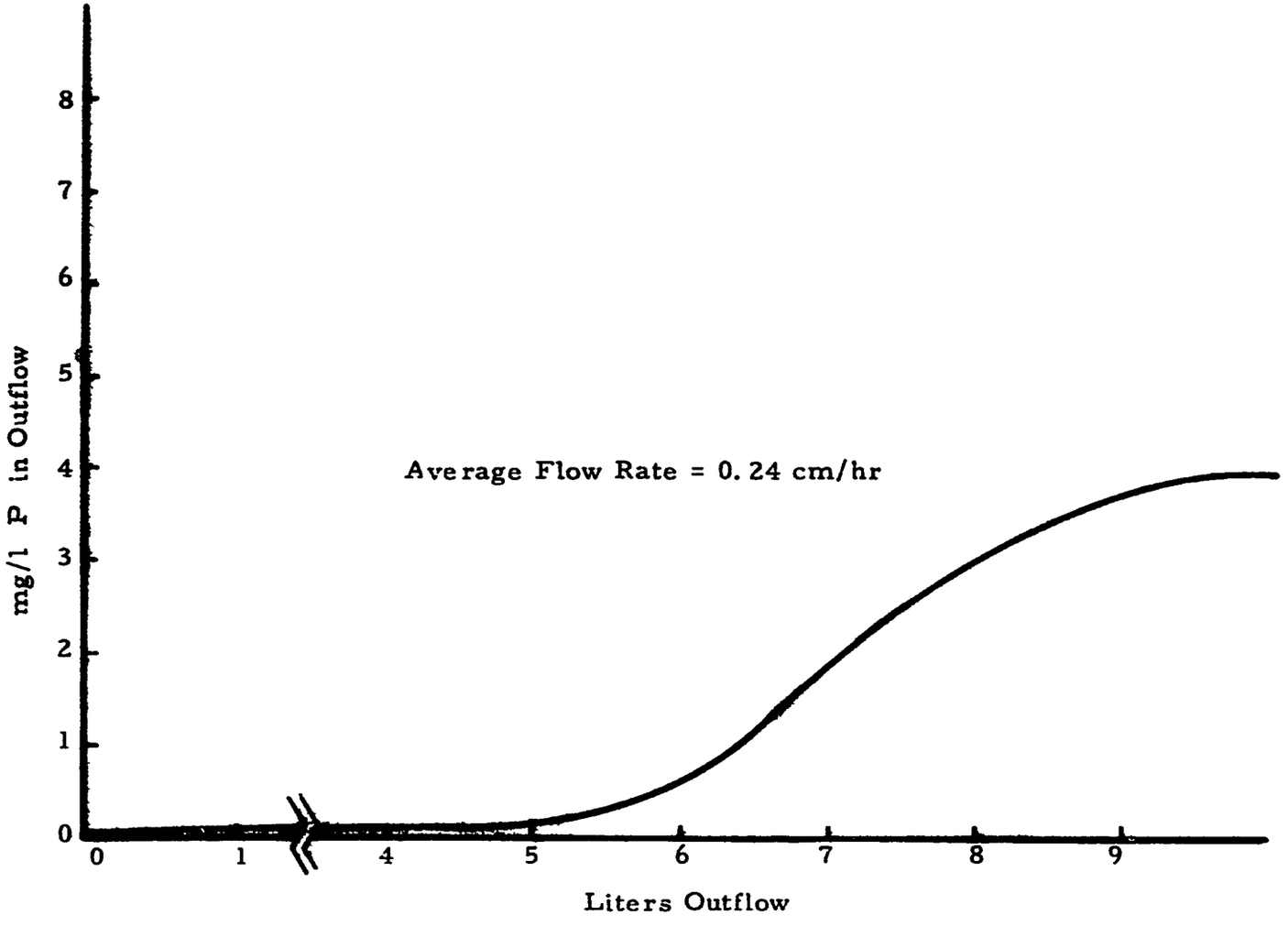


Figure 23. Phosphorus Breakthrough Curve from Soil Column Test 6, Draper Soil Profile.

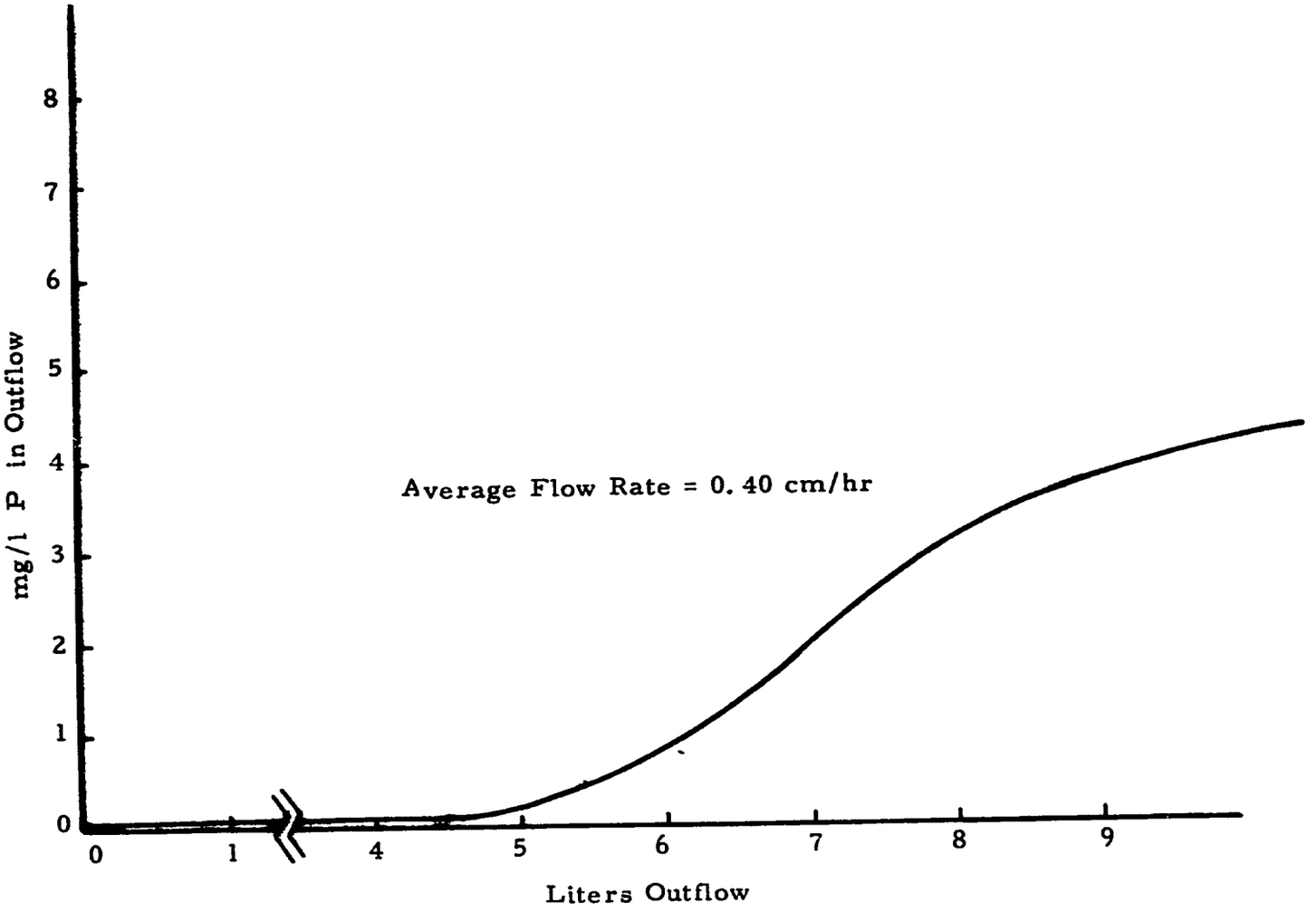


Figure 24 Phosphorus Breakthrough Curve from Soil Column Test 7, Draper Soil Profile.

Appendix C

Adsorption Test Data

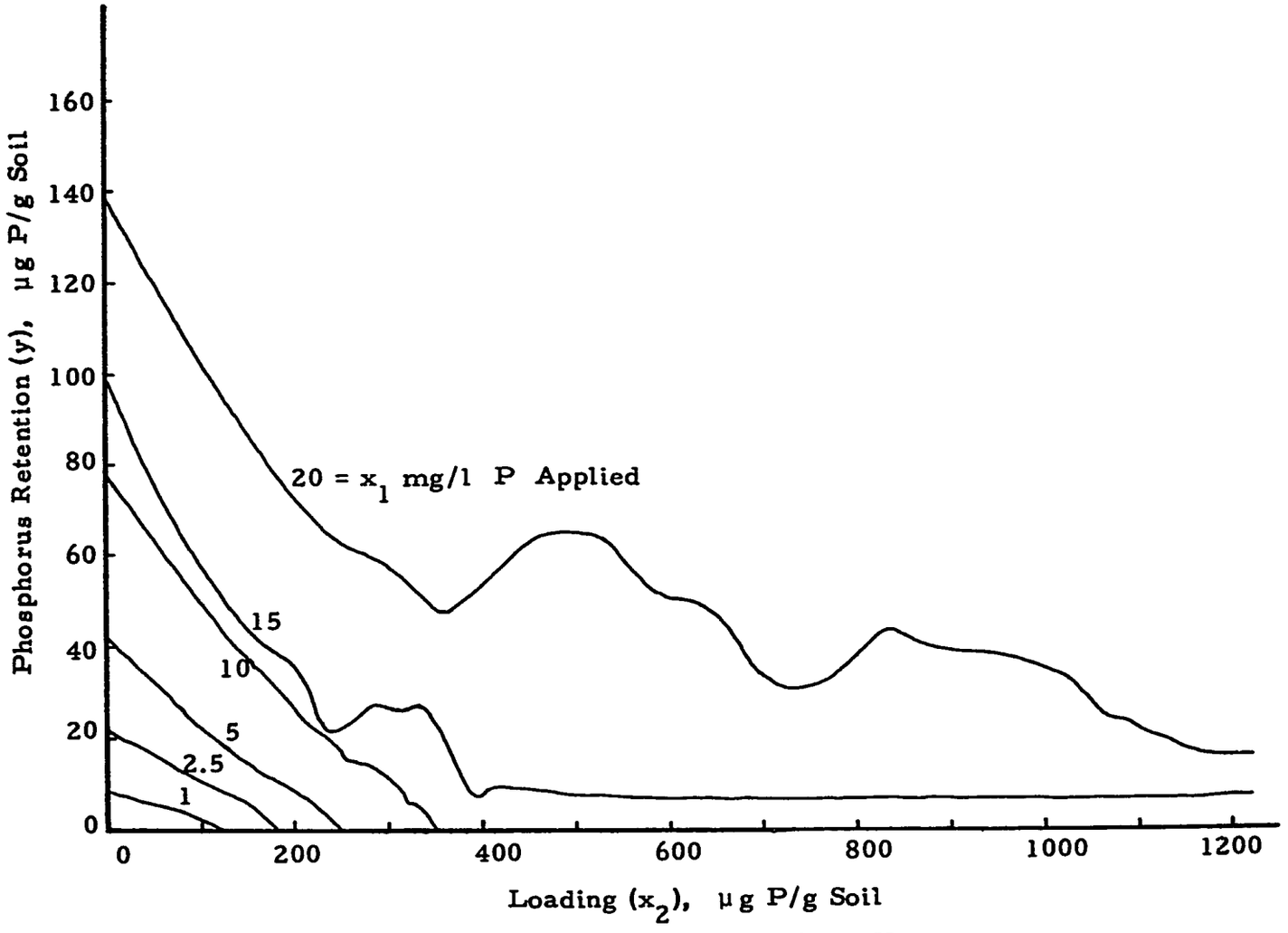


Figure 25. Repeated Adsorption Data for Draper 0-6 in. Horizon.

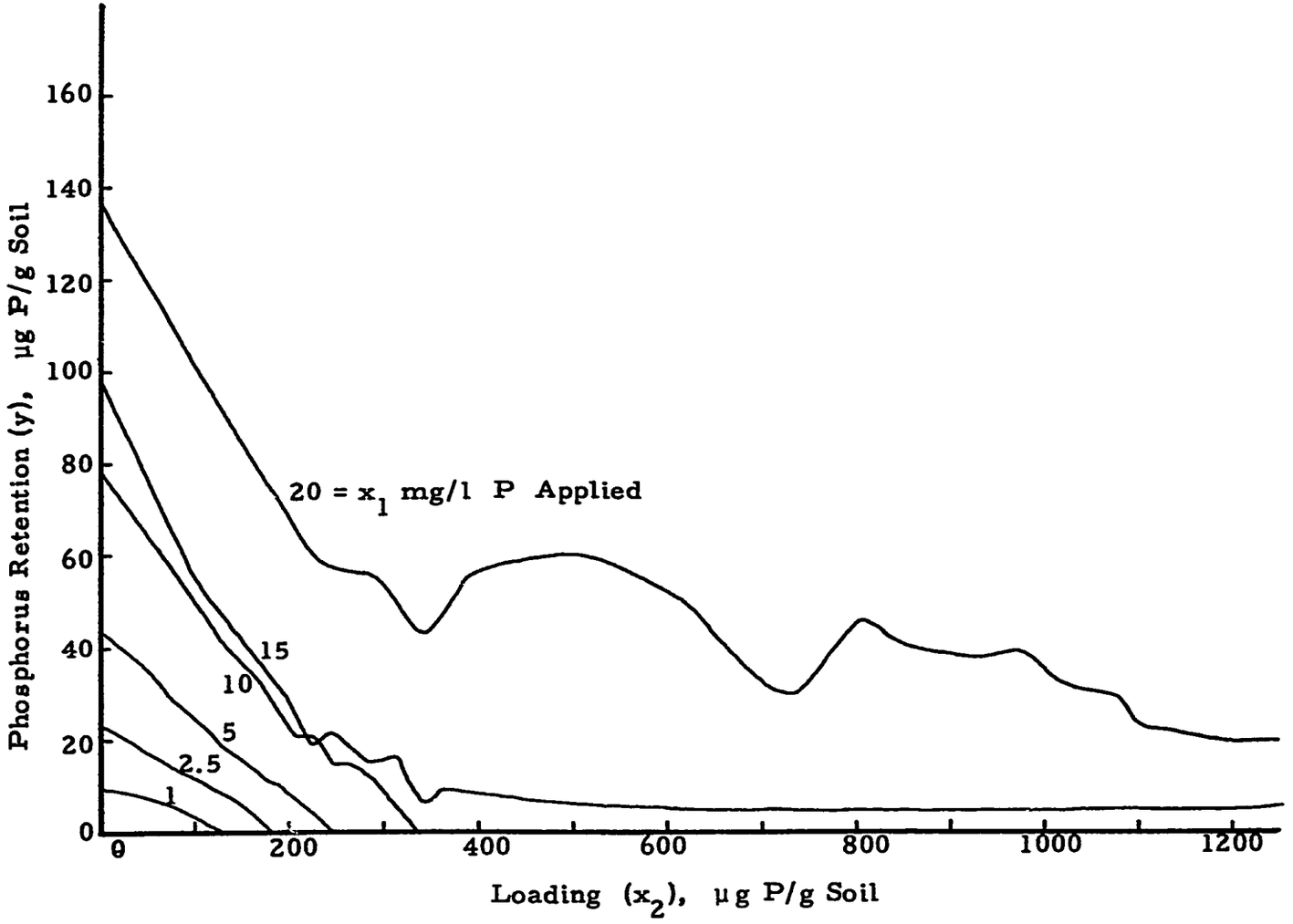


Figure 26. Repeated Adsorption Data for Draper 6-16 in. Horizon.

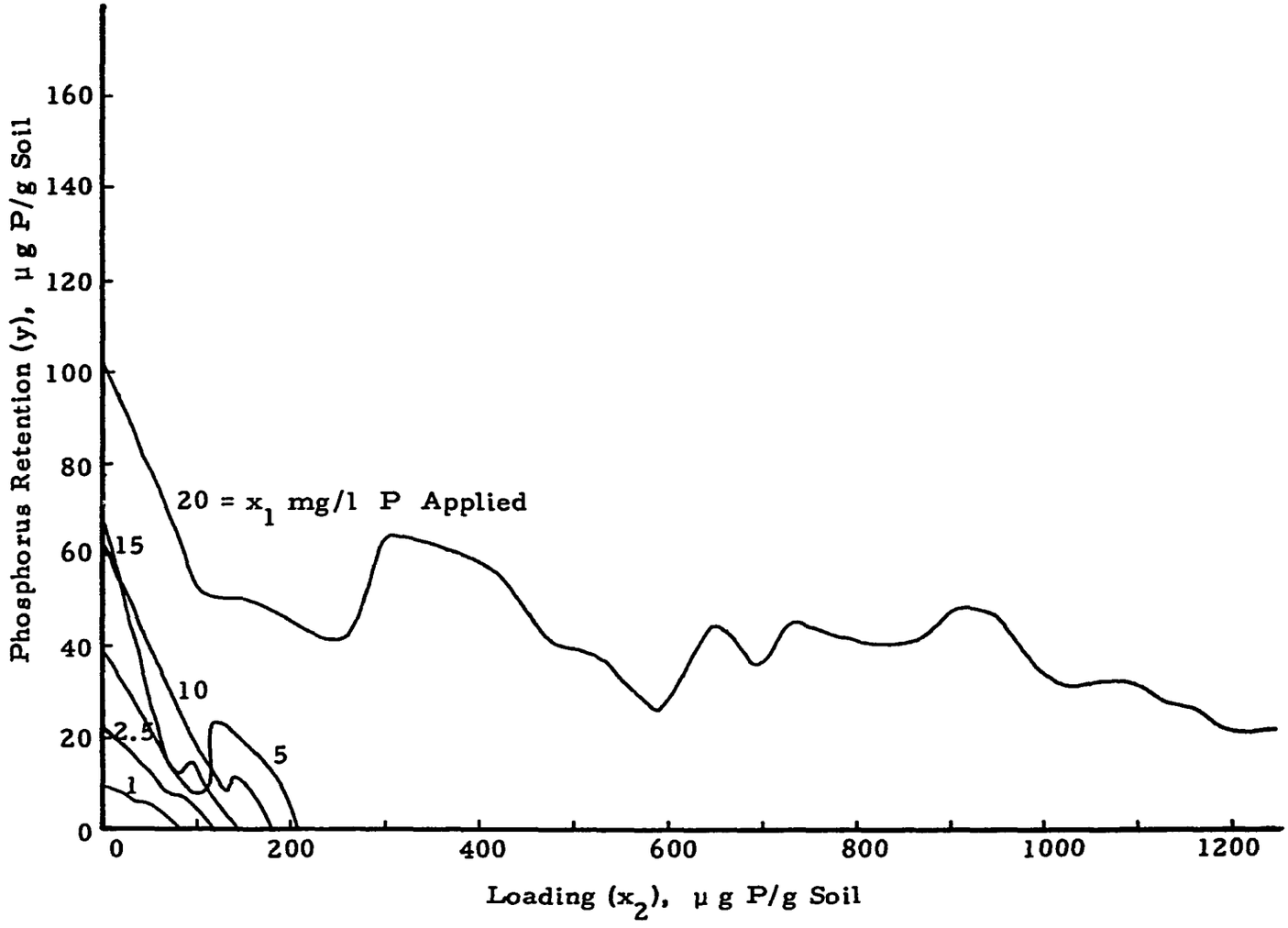


Figure 27. Repeated Adsorption Data for Draper 16-26 in. Horizon.

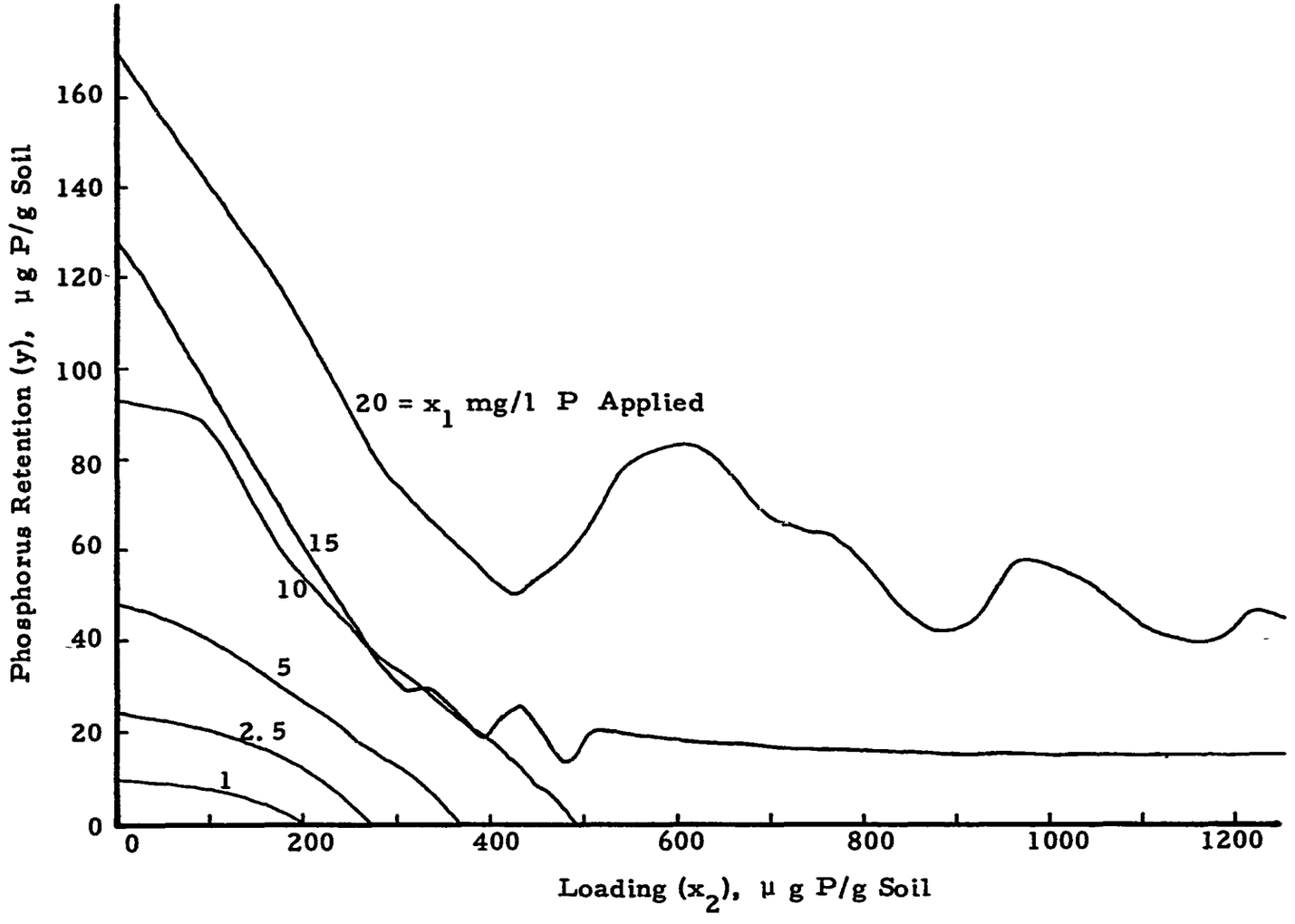


Figure 28. Repeated Adsorption Data for Draper 26-37 in. Horizon.

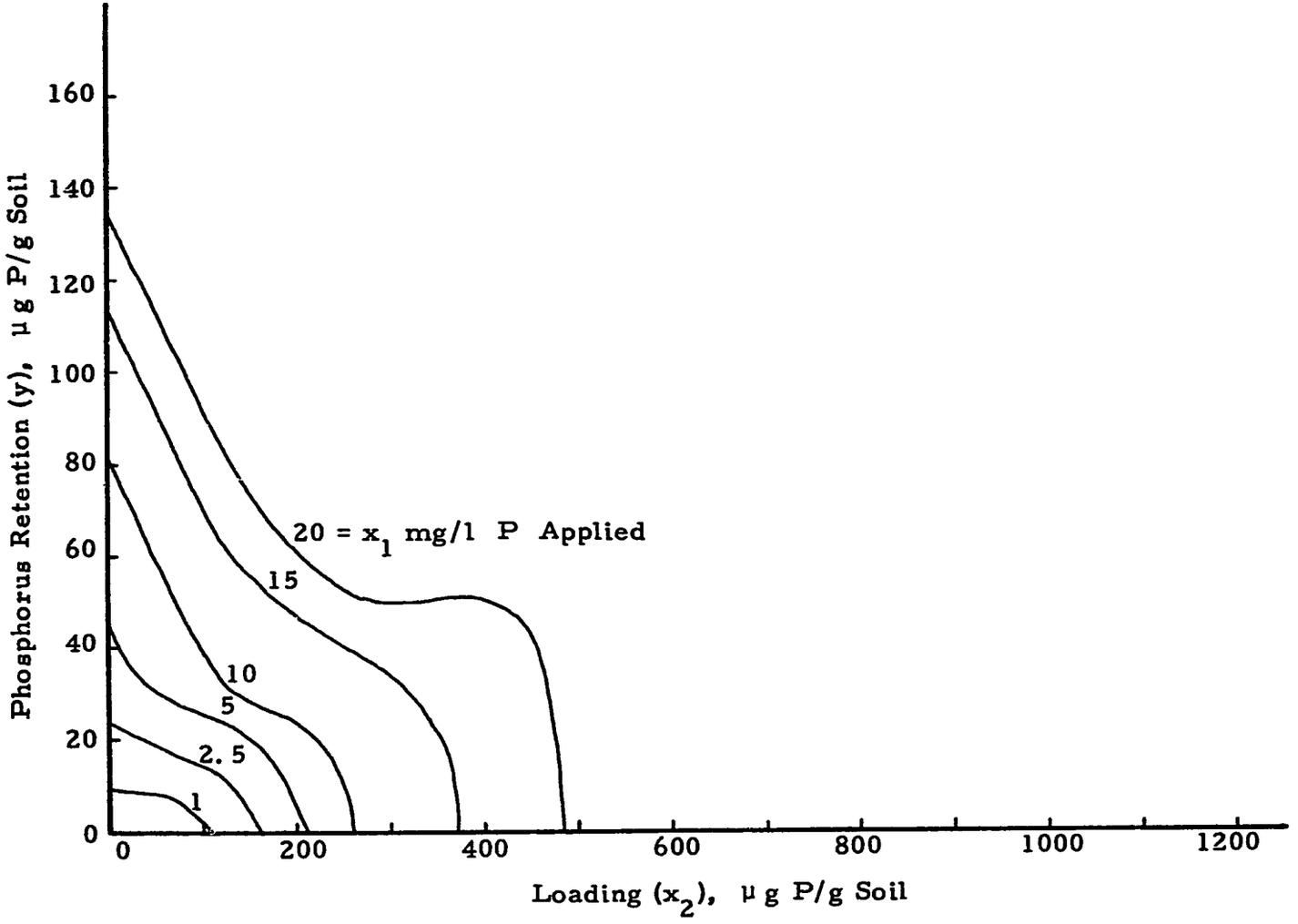


Figure 29. Repeated Adsorption Data for Kilburn 11-24 in. Horizon.

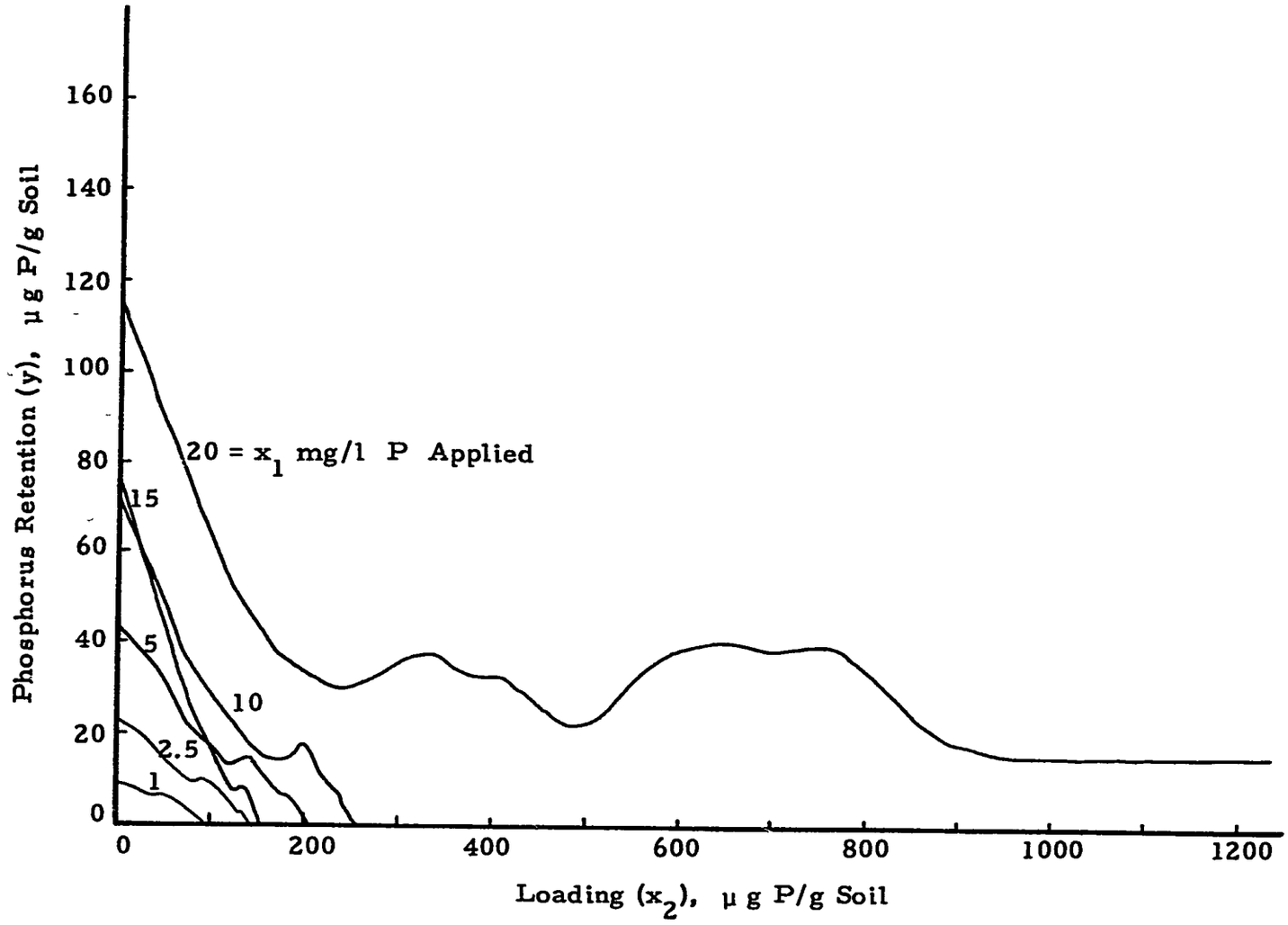


Figure 30. Repeated Adsorption Data for Kilburn 24-60 in. Horizon.

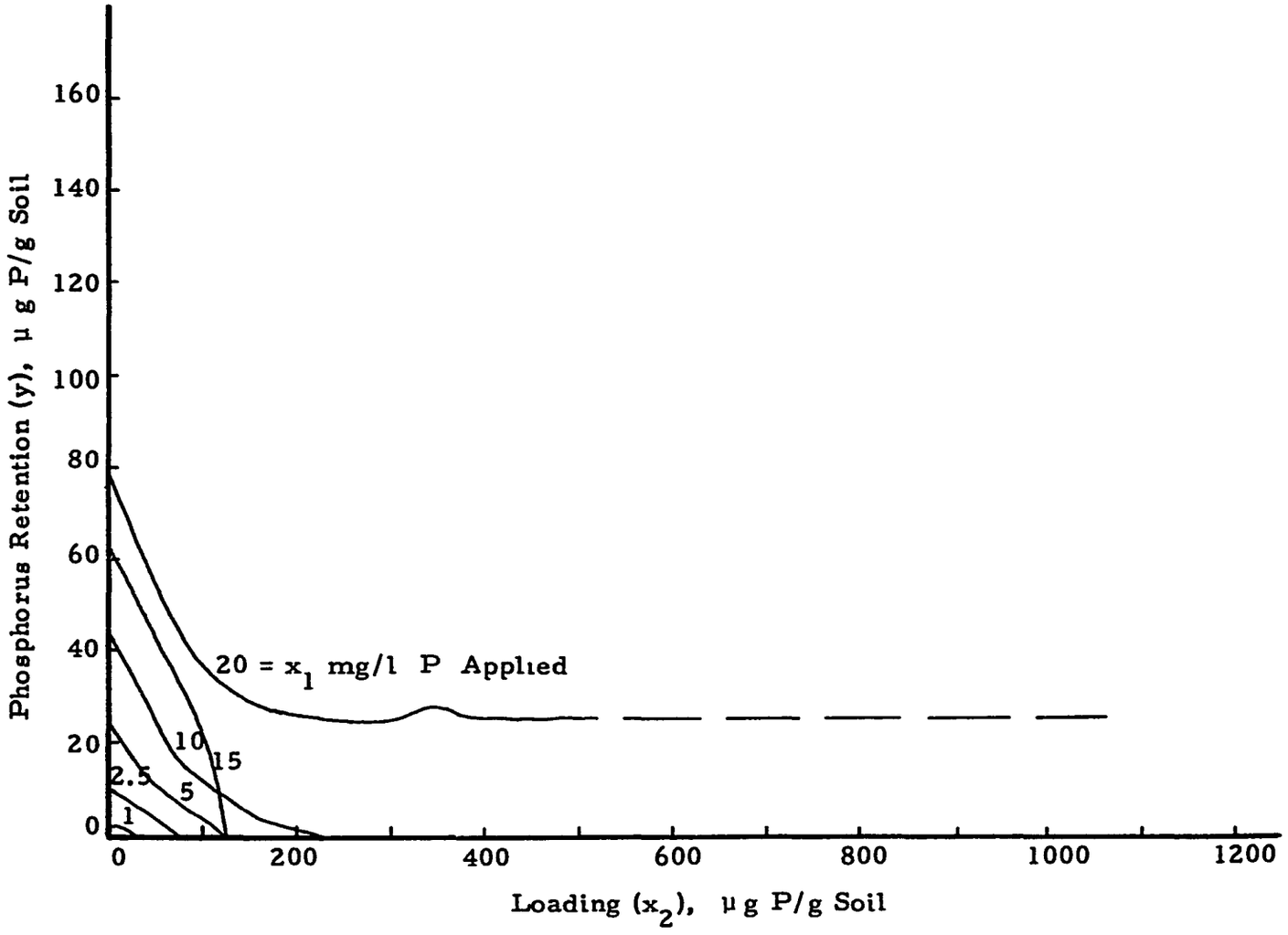


Figure 31. Repeated Adsorption Data for Parleys 0-6 in. Horizon.

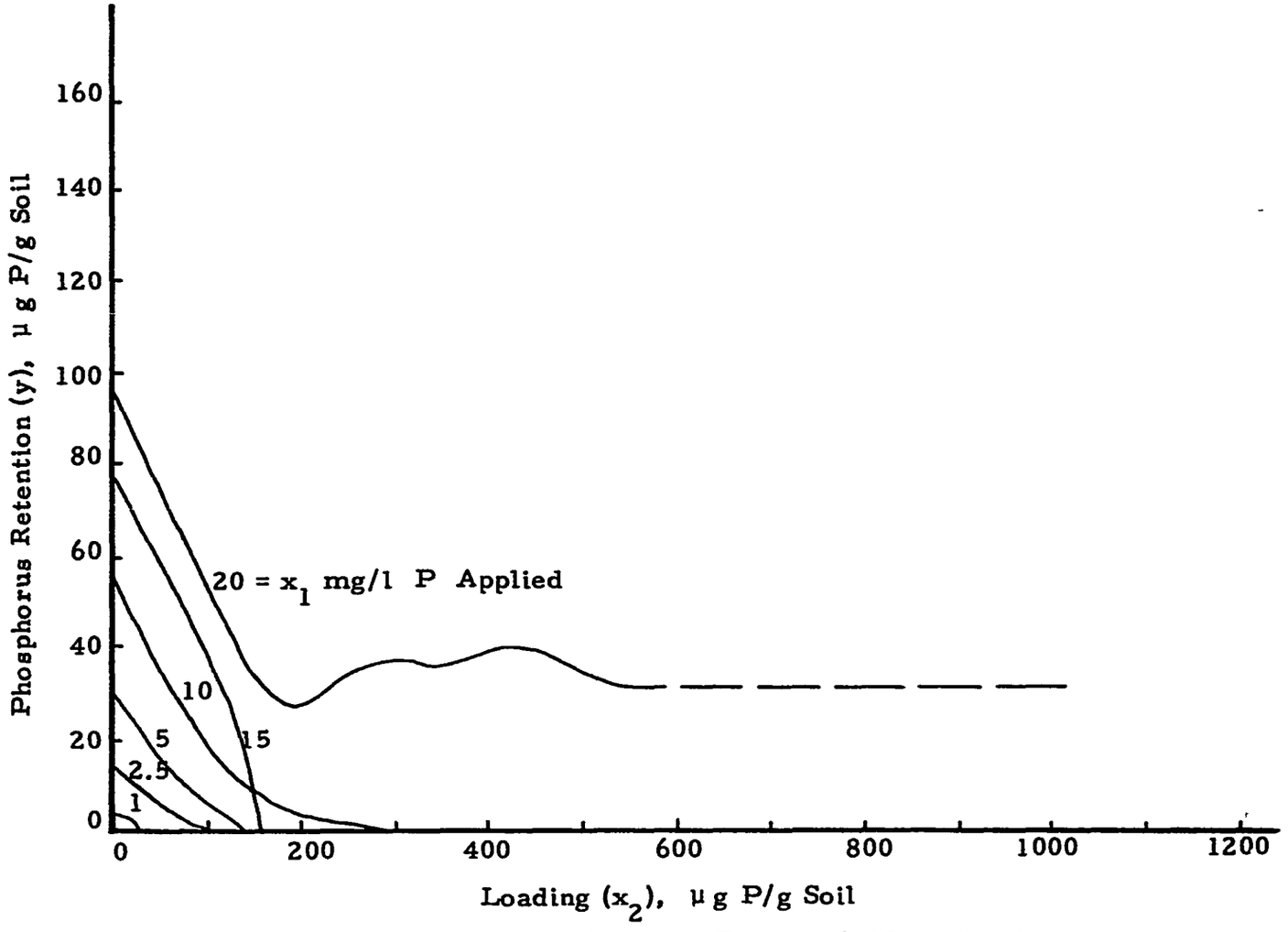


Figure 32. Repeated Adsorption Data for Parleys 6-15 in. Horizon.

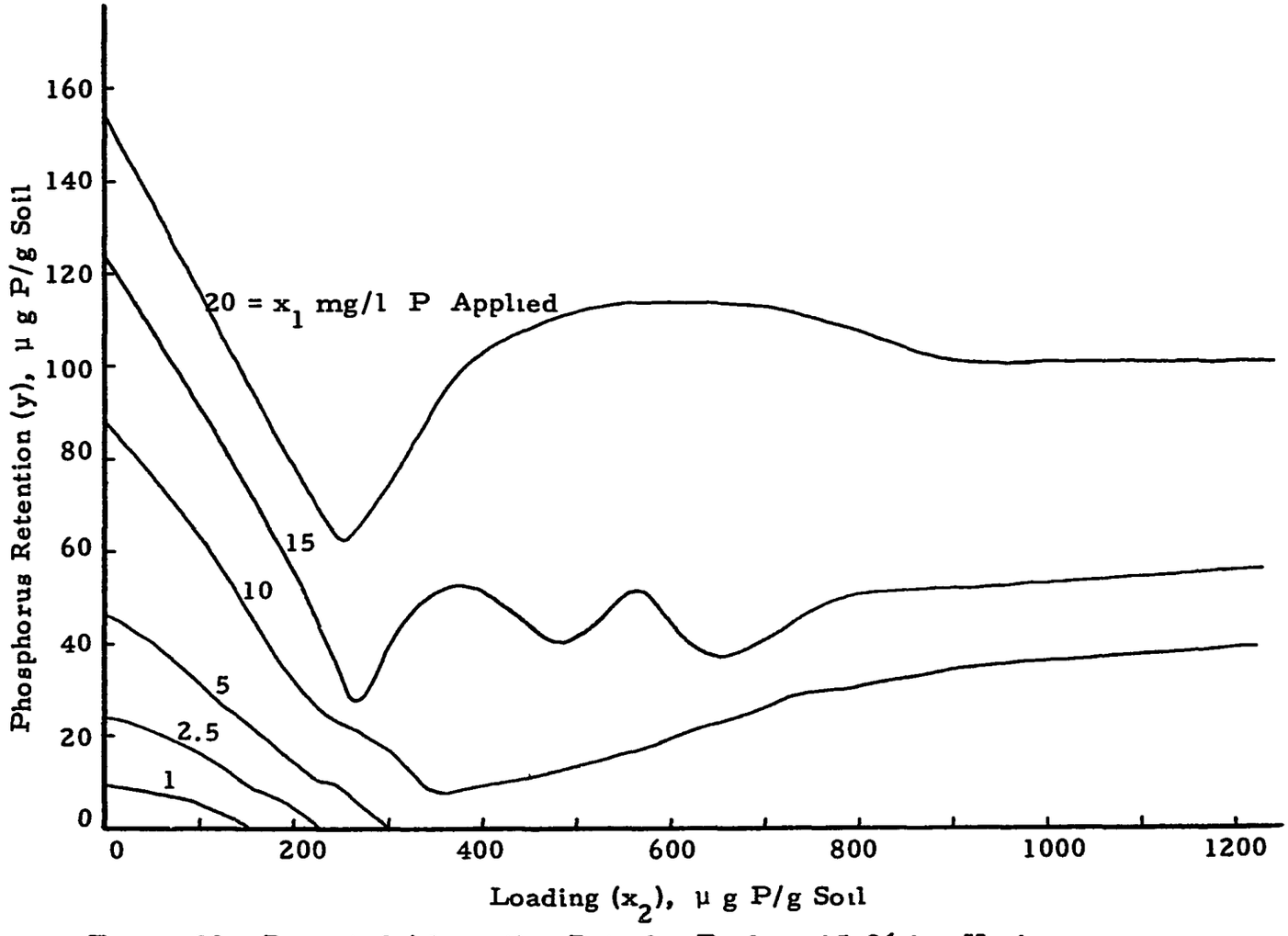


Figure 33. Repeated Adsorption Data for Parleys 15-26 in. Horizon.

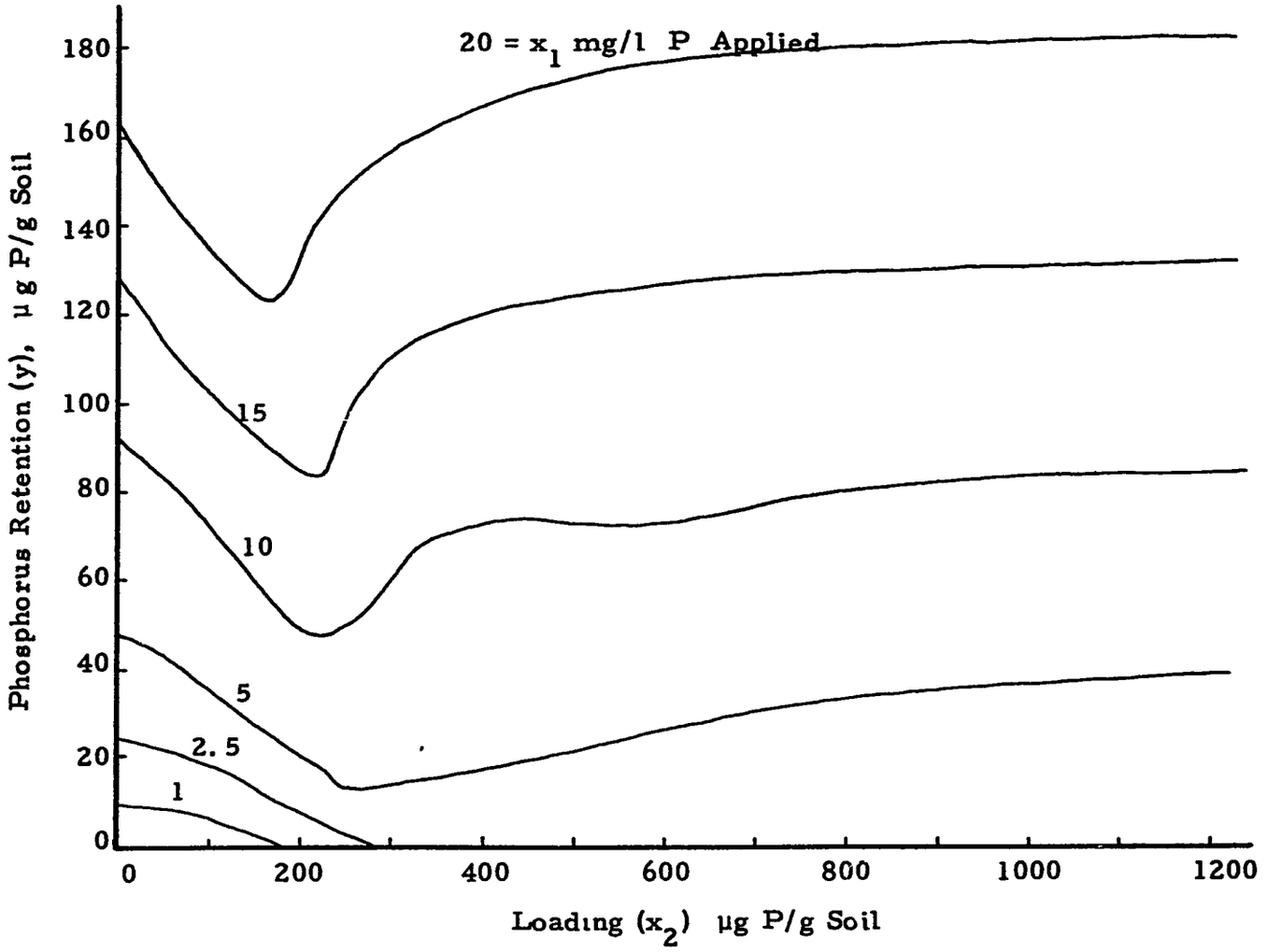


Figure 34. Repeated Adsorption Data for Parleys 26-33 in. Horizon.

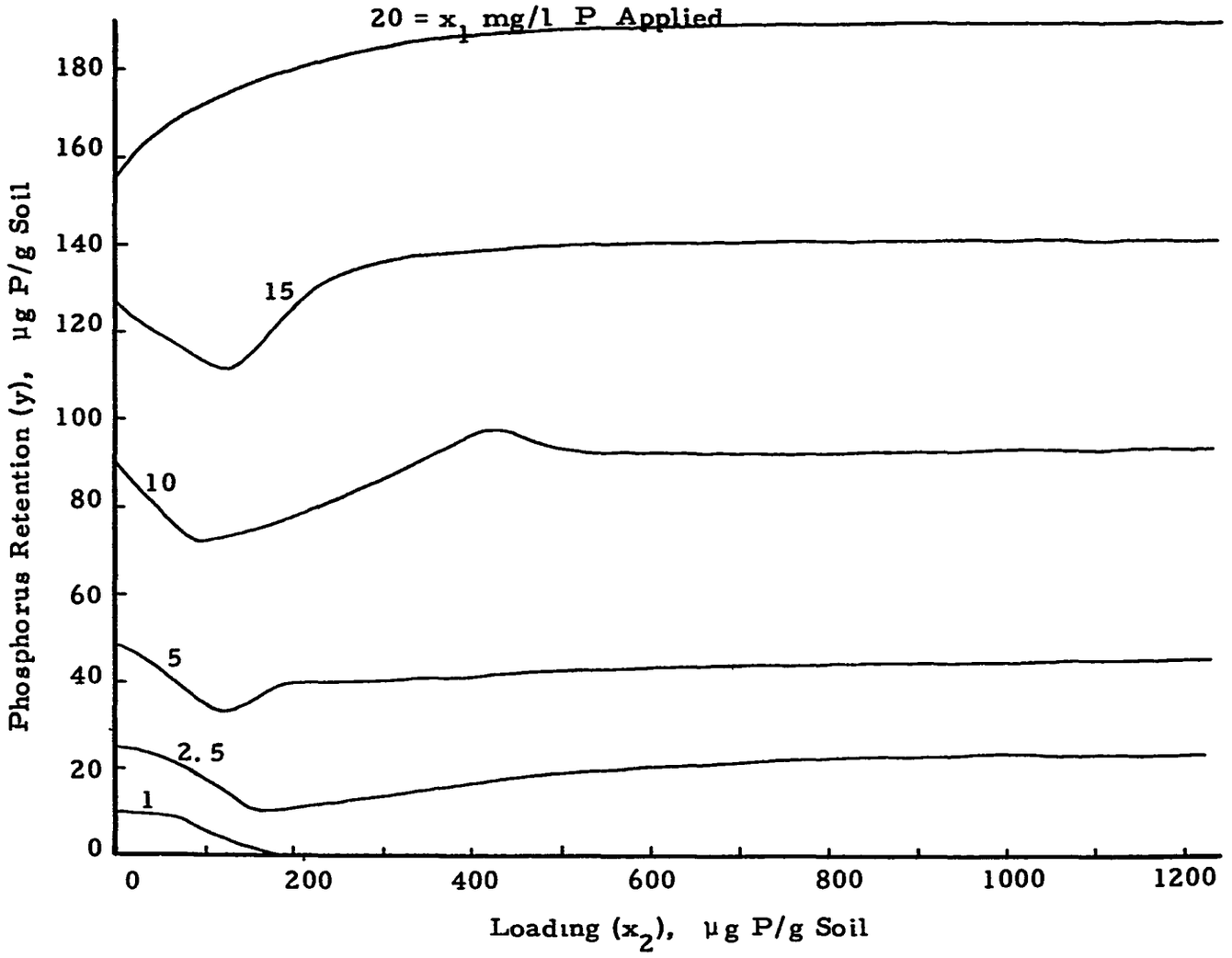


Figure 35. Repeated Adsorption Data for Parleys 33-60 in. Horizon.

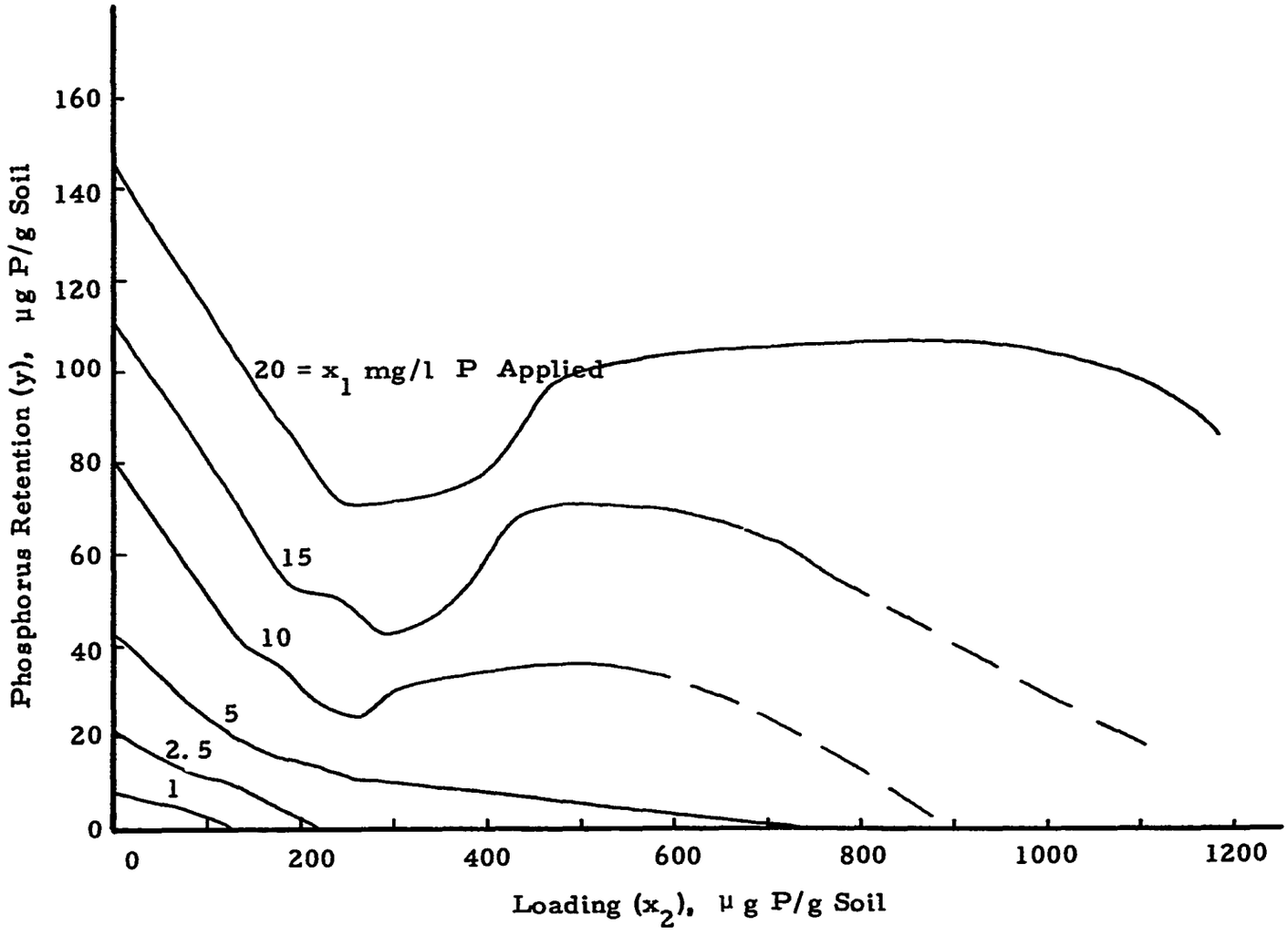


Figure 36. Repeated Adsorption Data for Nibley 0-7 in. Horizon.

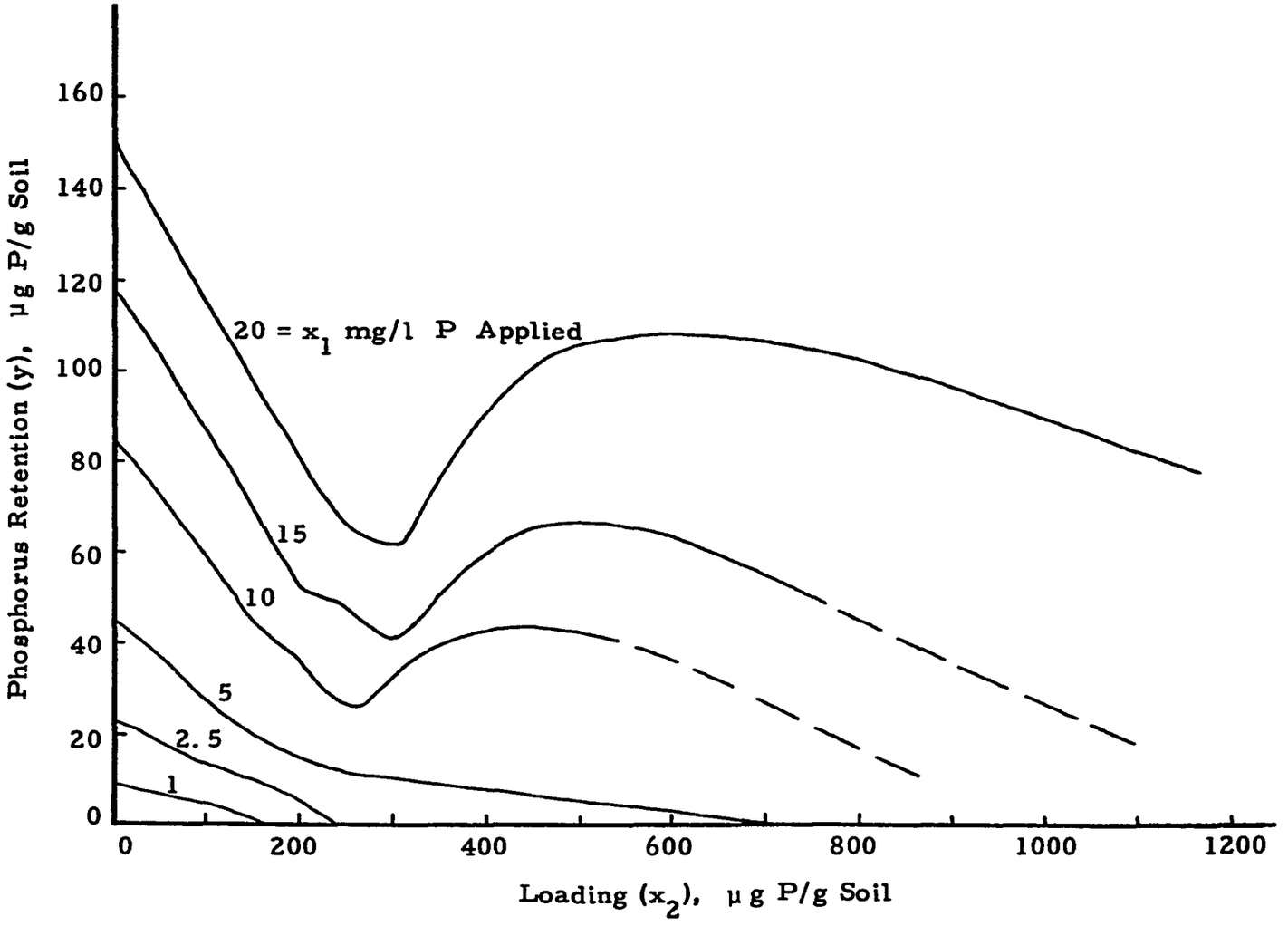


Figure 37. Repeated Adsorption Data for Nibley 7-13 in. Horizon.

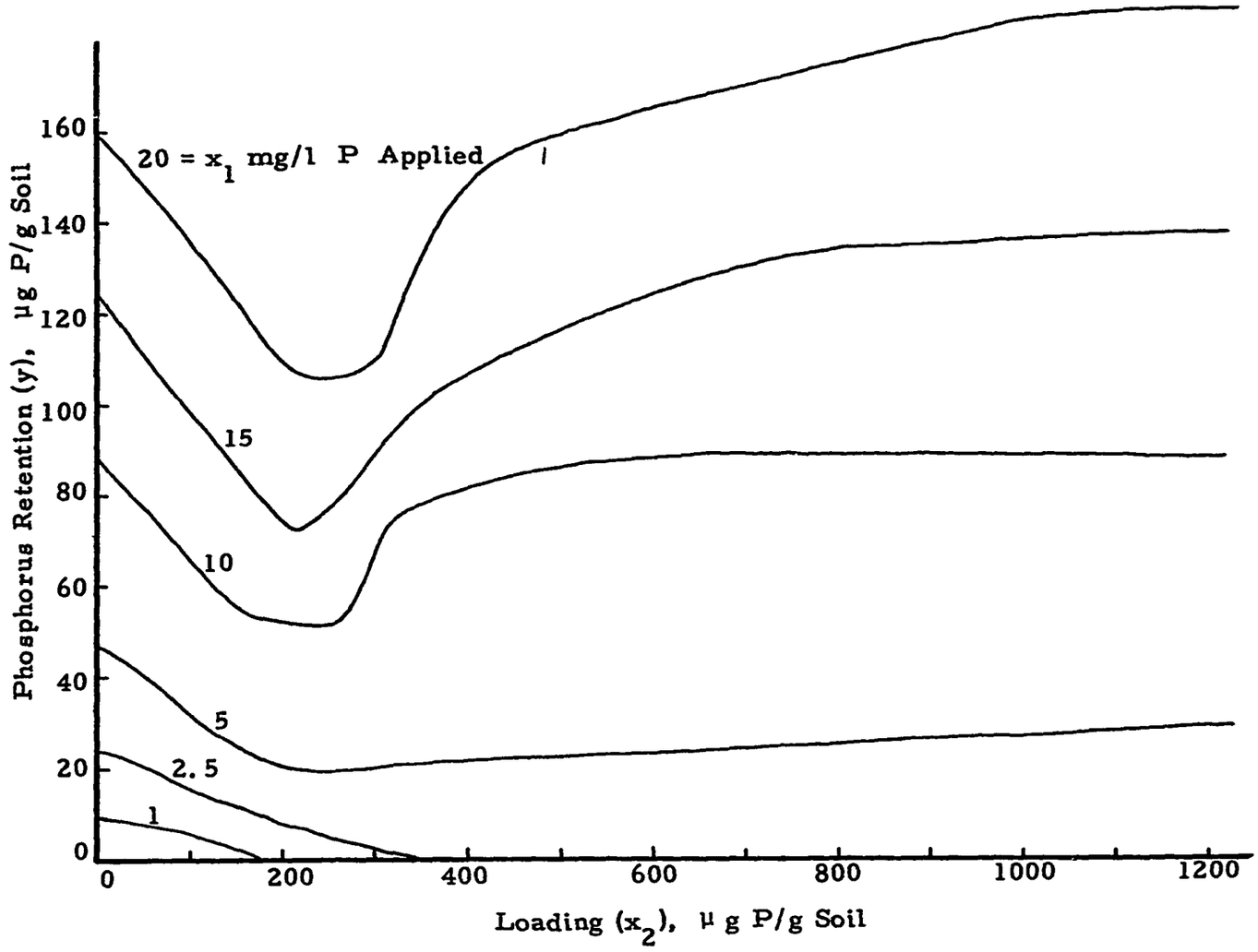


Figure 38. Repeated Adsorption Data for Nibley 13-20 in. Horizon.

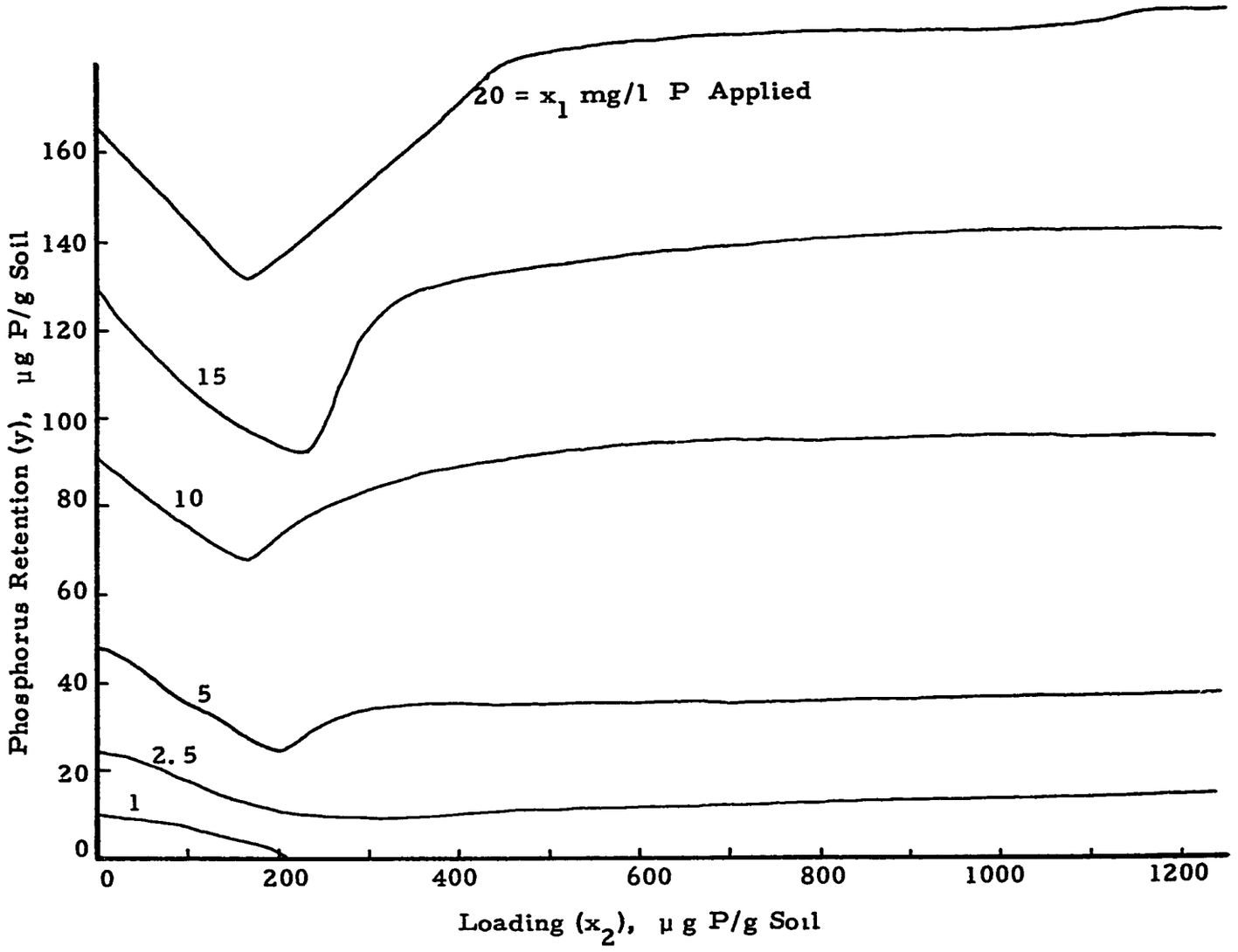


Figure 39. Repeated Adsorption Data for Nibley 20-32 in. Horizon.

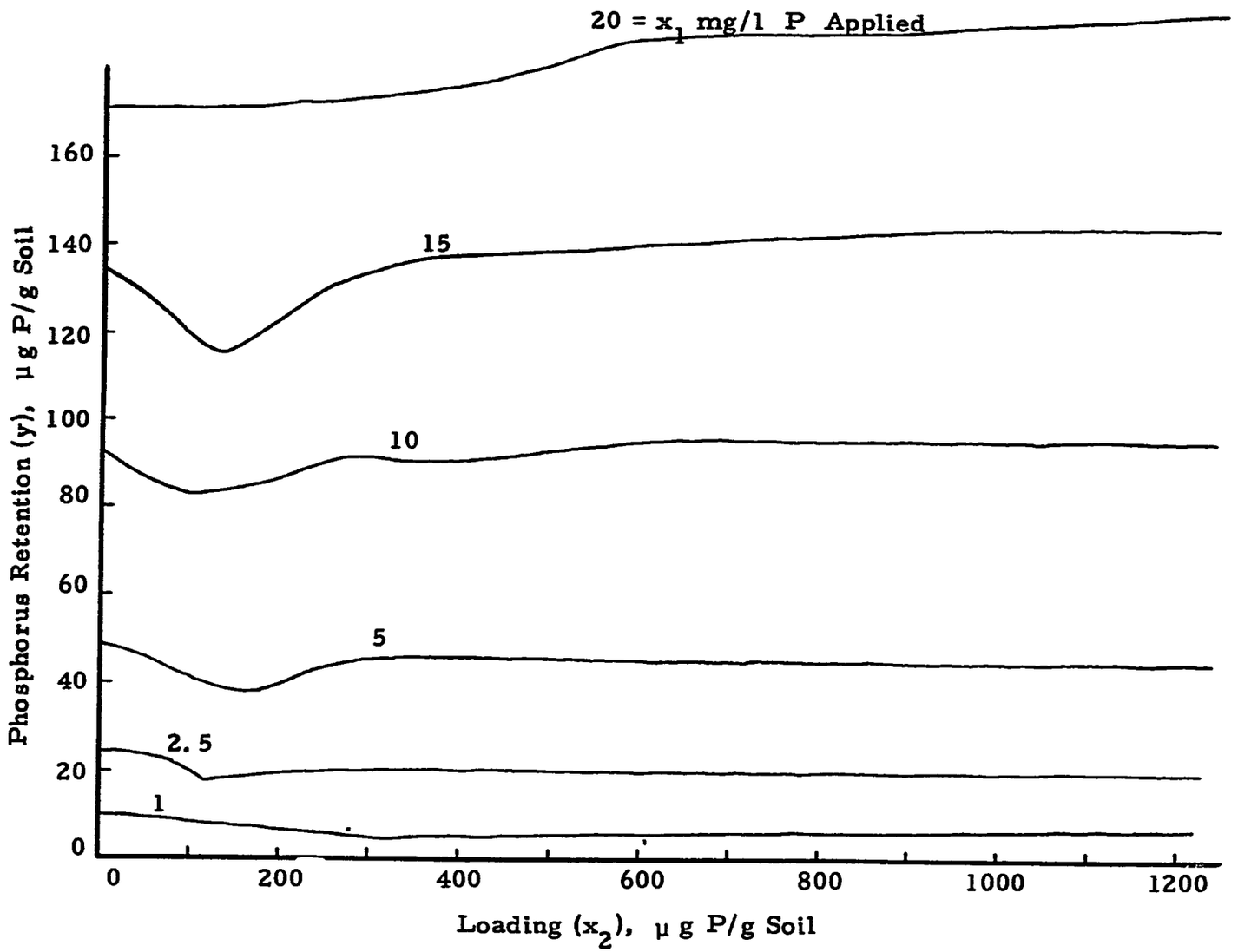


Figure 40. Repeated Adsorption Data for Nibley 32-43 in. Horizon.

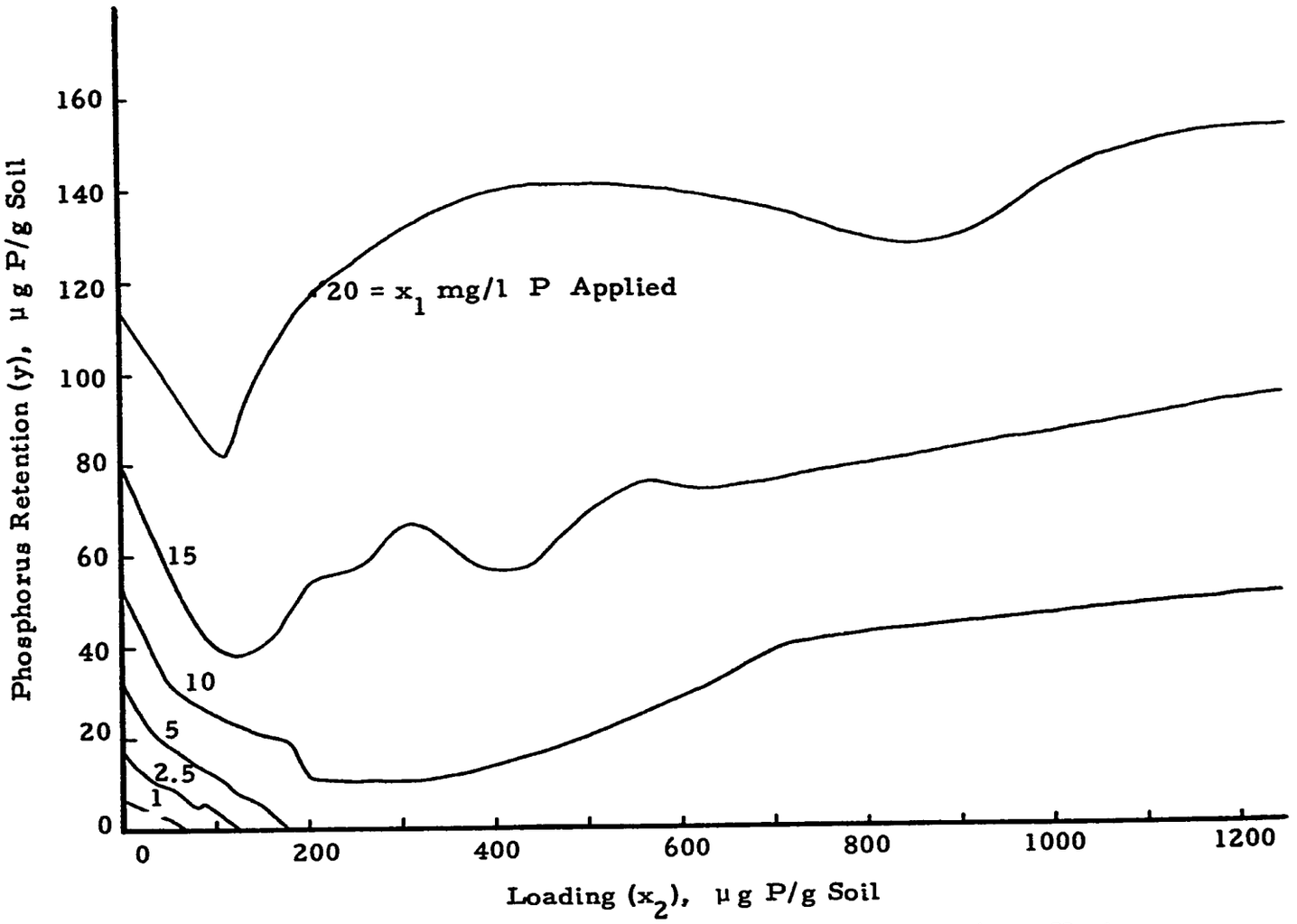


Figure 41. Repeated Adsorption Data for Warm Springs 0-6 in. Horizon.

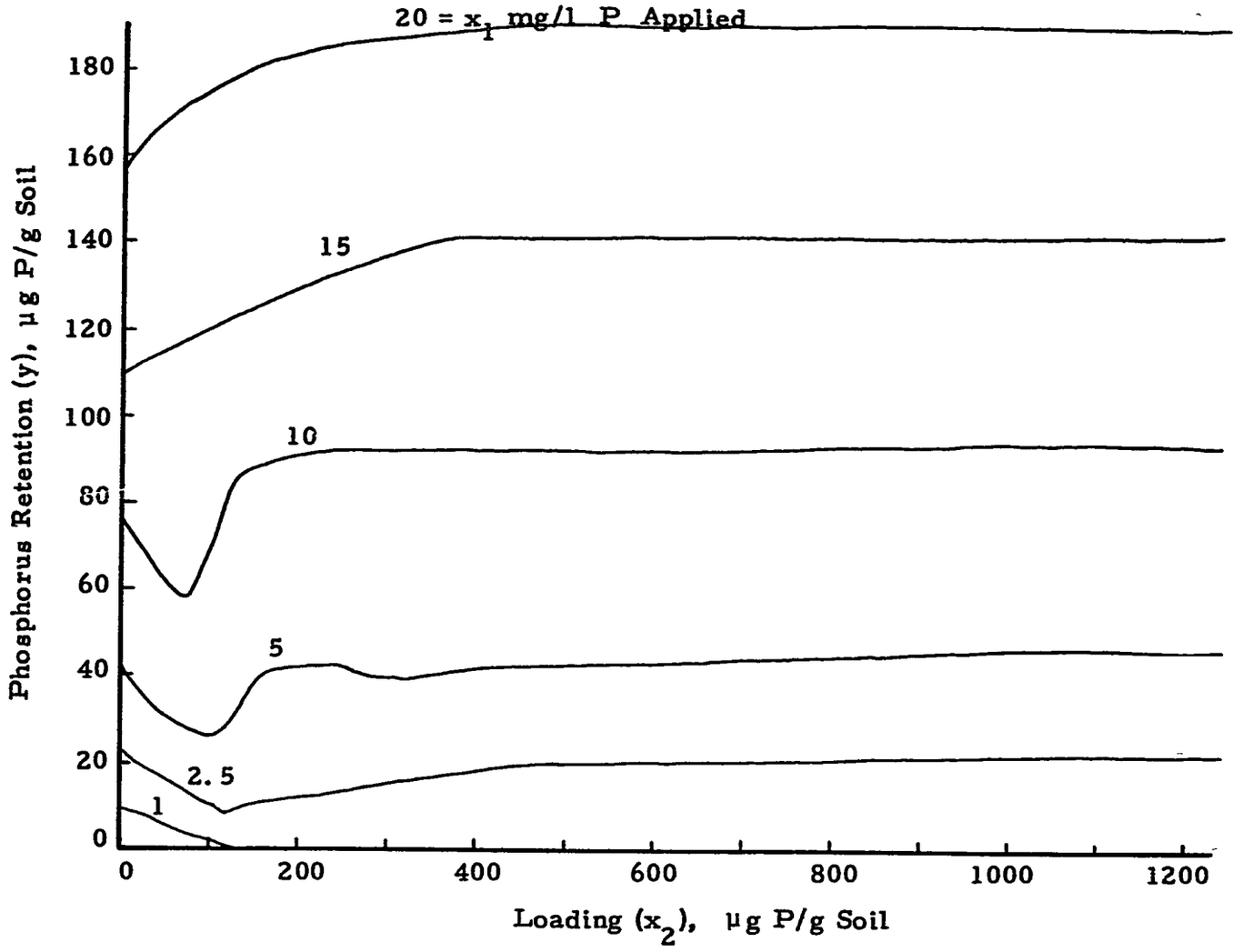


Figure 42. Repeated Adsorption Data for Warm Springs 6-37 in. Horizon.

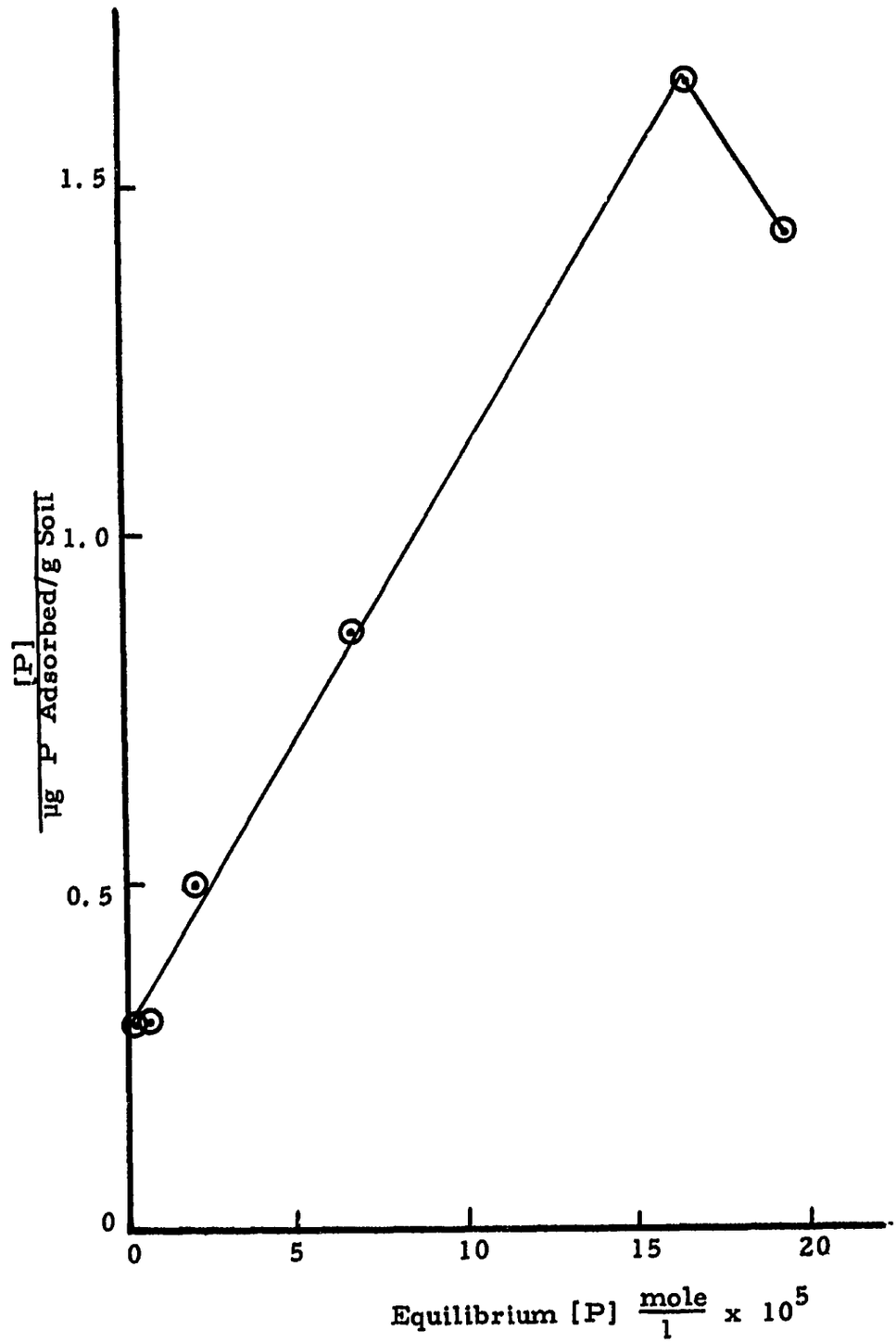


Figure 43. Langmuir Isotherm for Draper 6-16 in. Horizon.

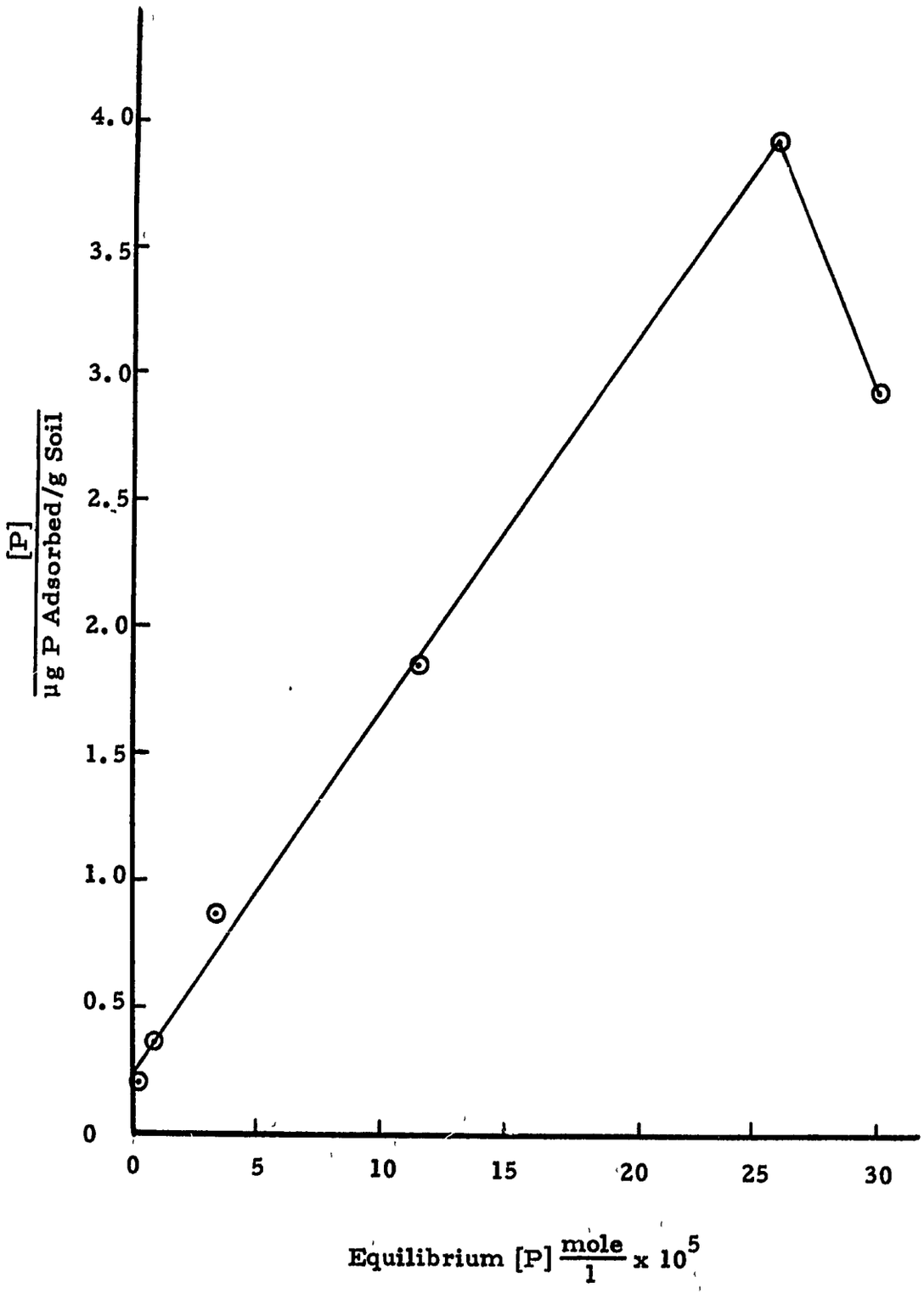


Figure 44. Langmuir Isotherm for Draper 16-26 in. Horizon.

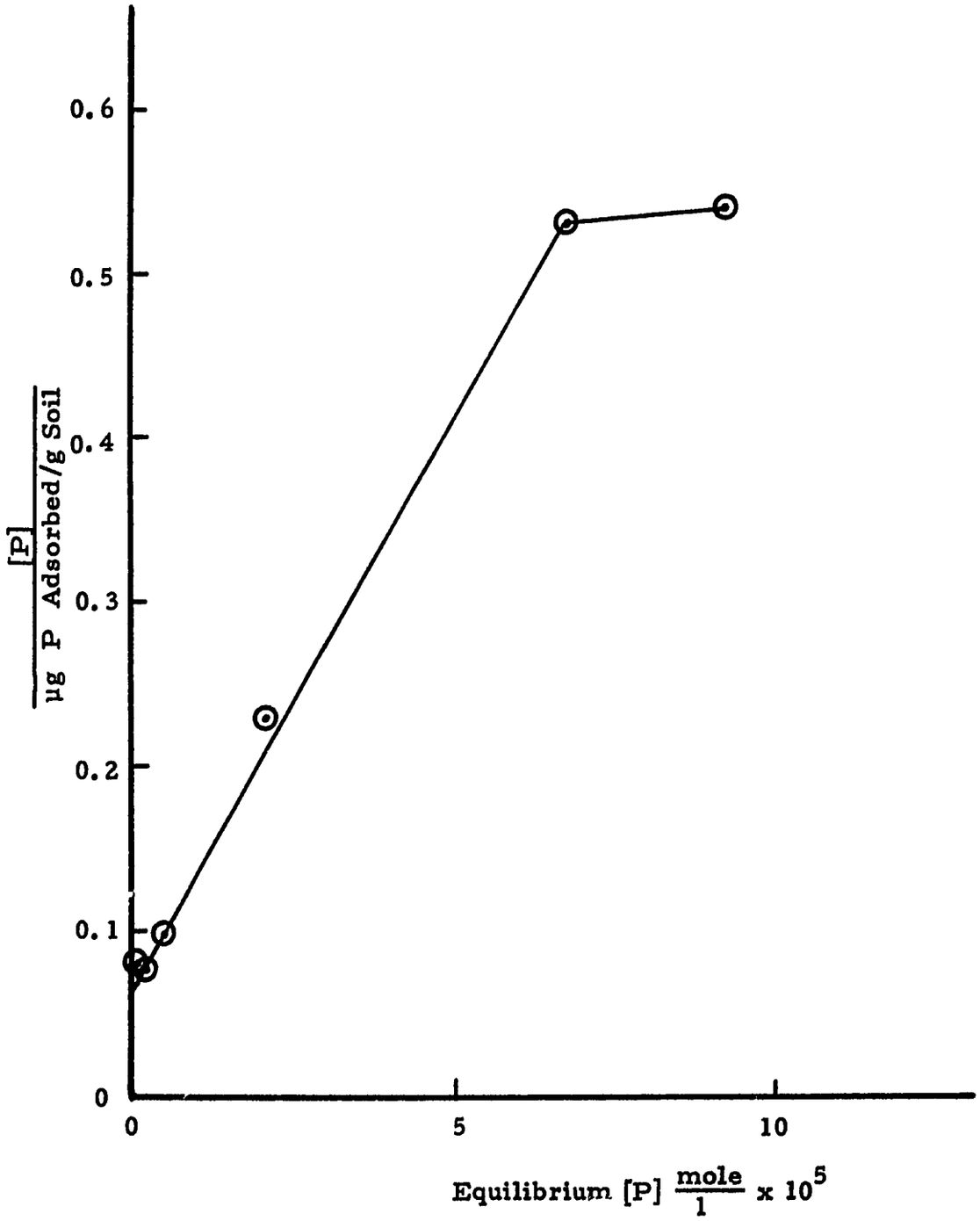


Figure 45. Langmuir Isotherm for Draper 26-37 in. Horizon.

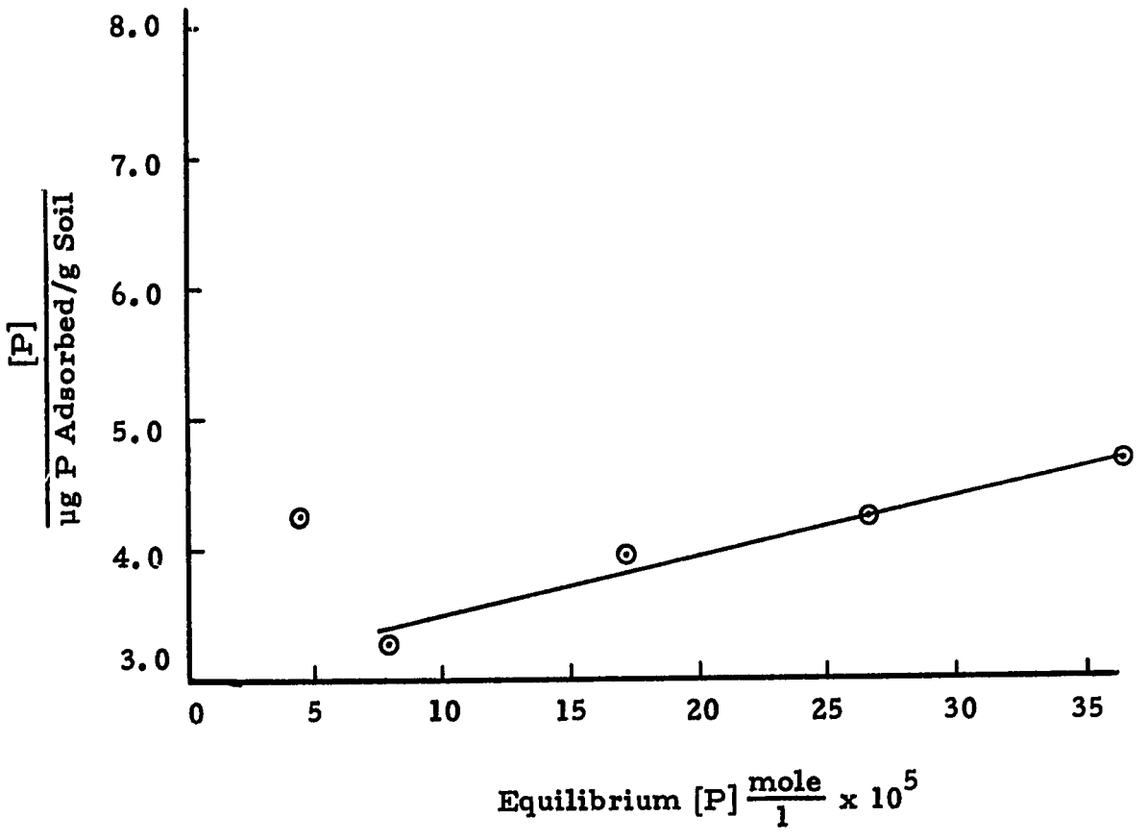


Figure 46. Langmuir Isotherm for Parleys 0-6 in. Horizon.

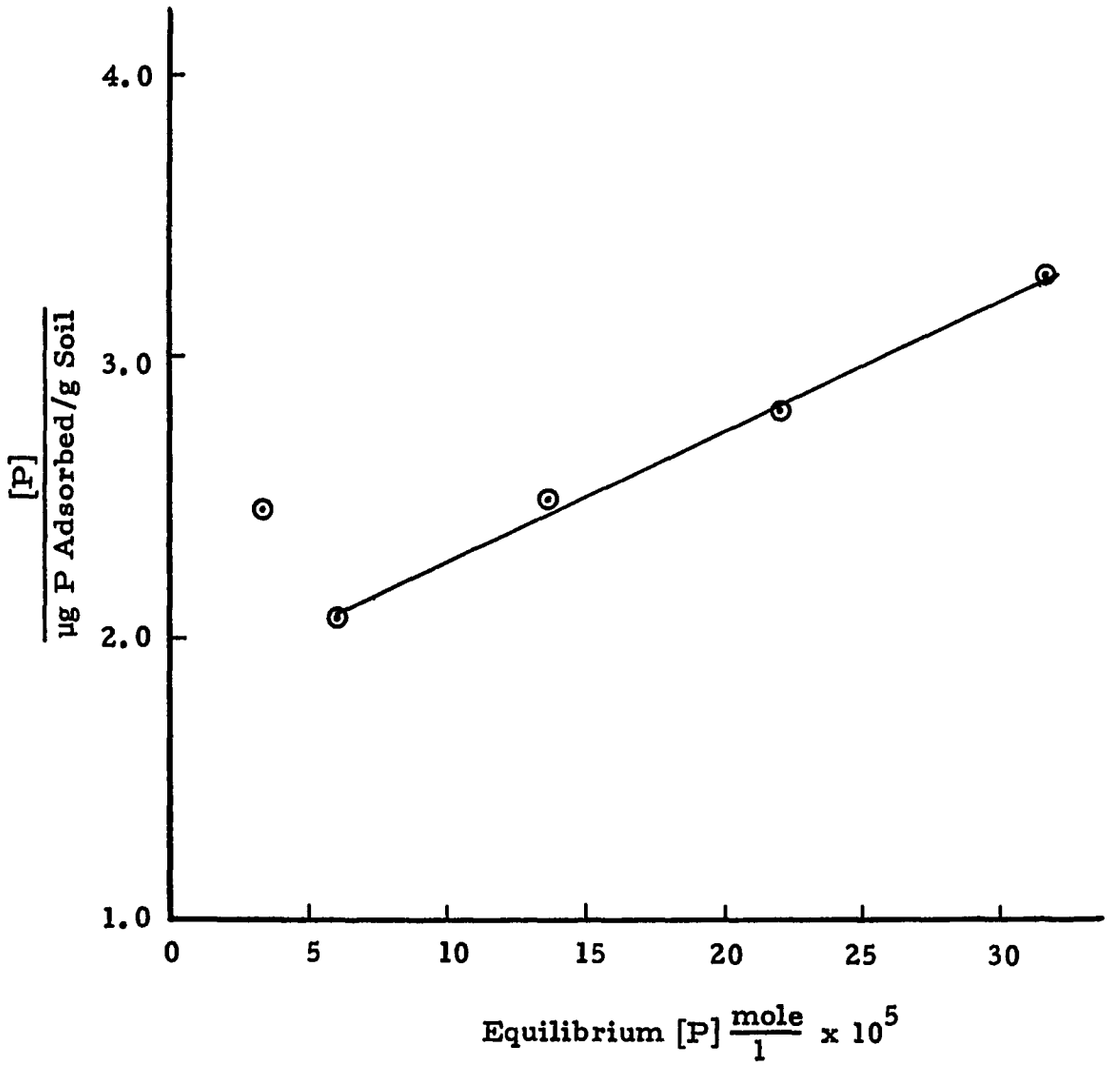


Figure 47. Langmuir Isotherm for Parleys 6-15 in. Horizon.

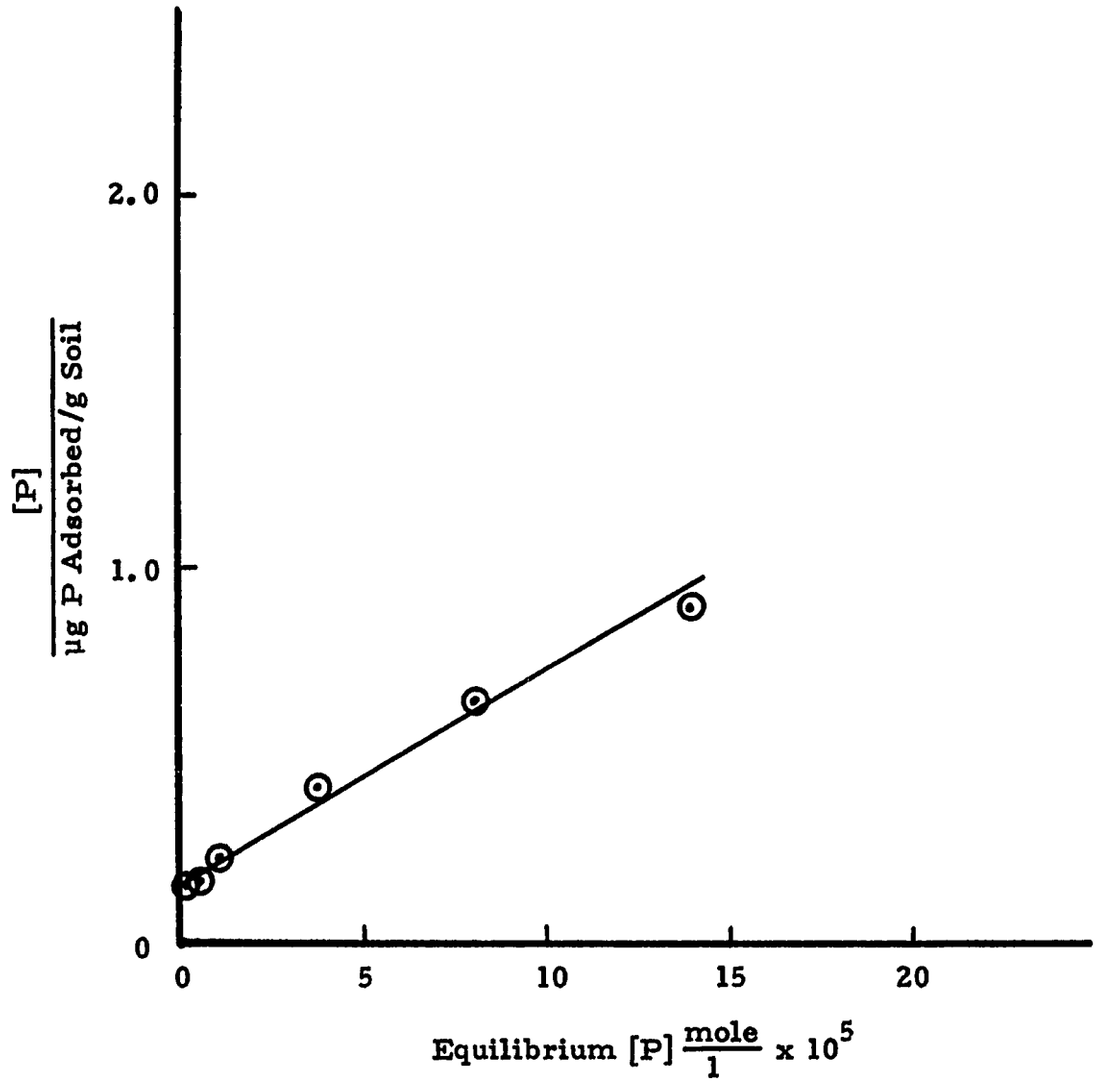


Figure 48. Langmuir Isotherm for Parleys 15-26 in. Horizon.

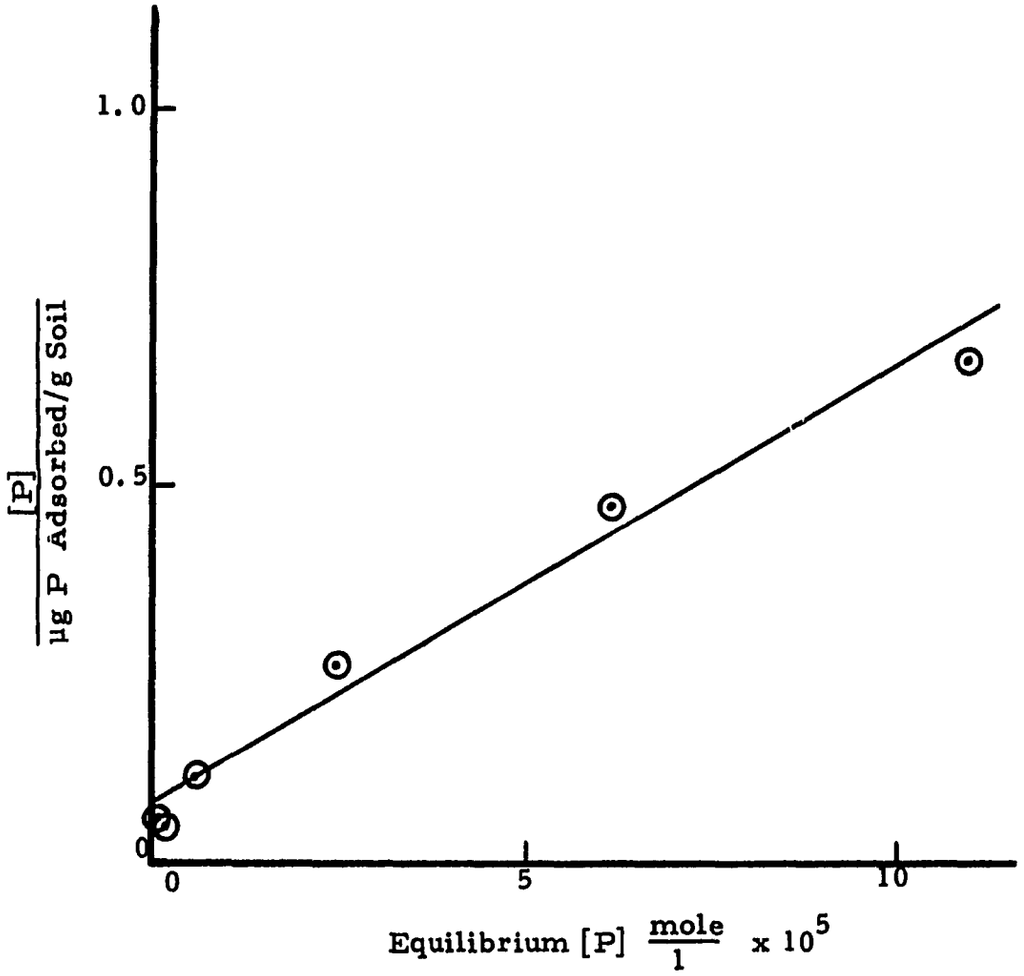


Figure 49. Langmuir Isotherm for Parleys 26-33 in. Horizon.

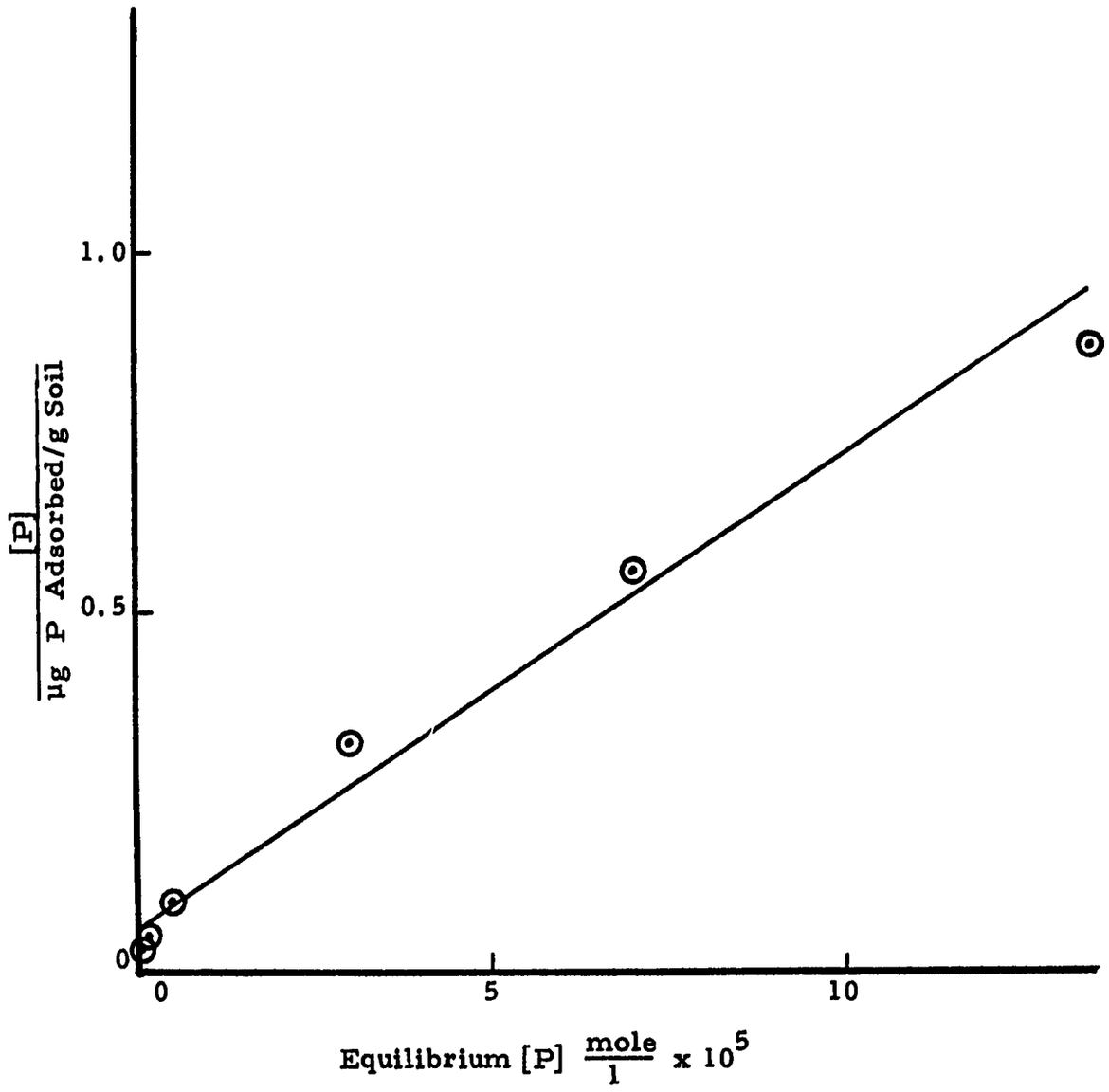


Figure 50. Langmuir Isotherm for Parleys 33-60 in. Horizon.

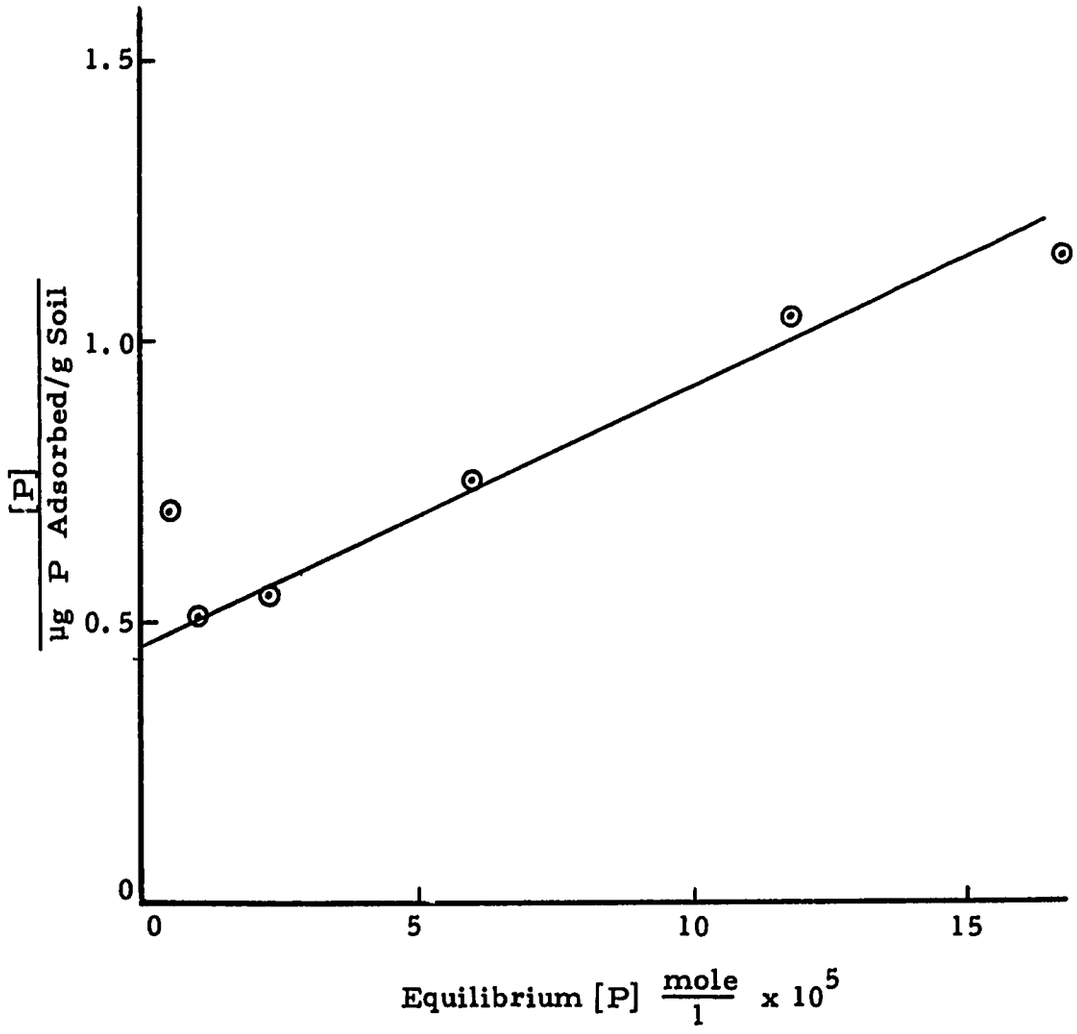


Figure 51. Langmuir Isotherm for Nibley 0-7 in. Horizon.

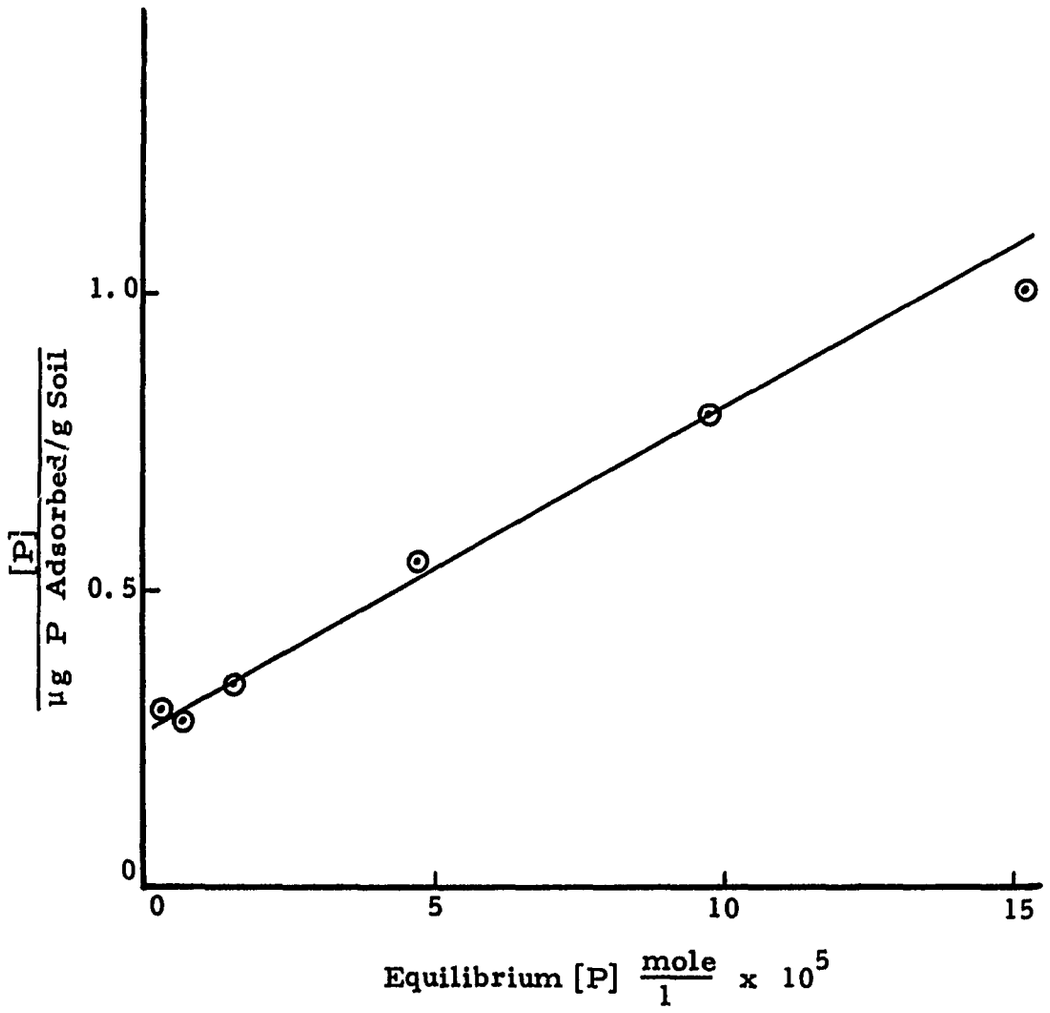


Figure 52. Langmuir Isotherm for Nibley 7-13 in. Horizon.

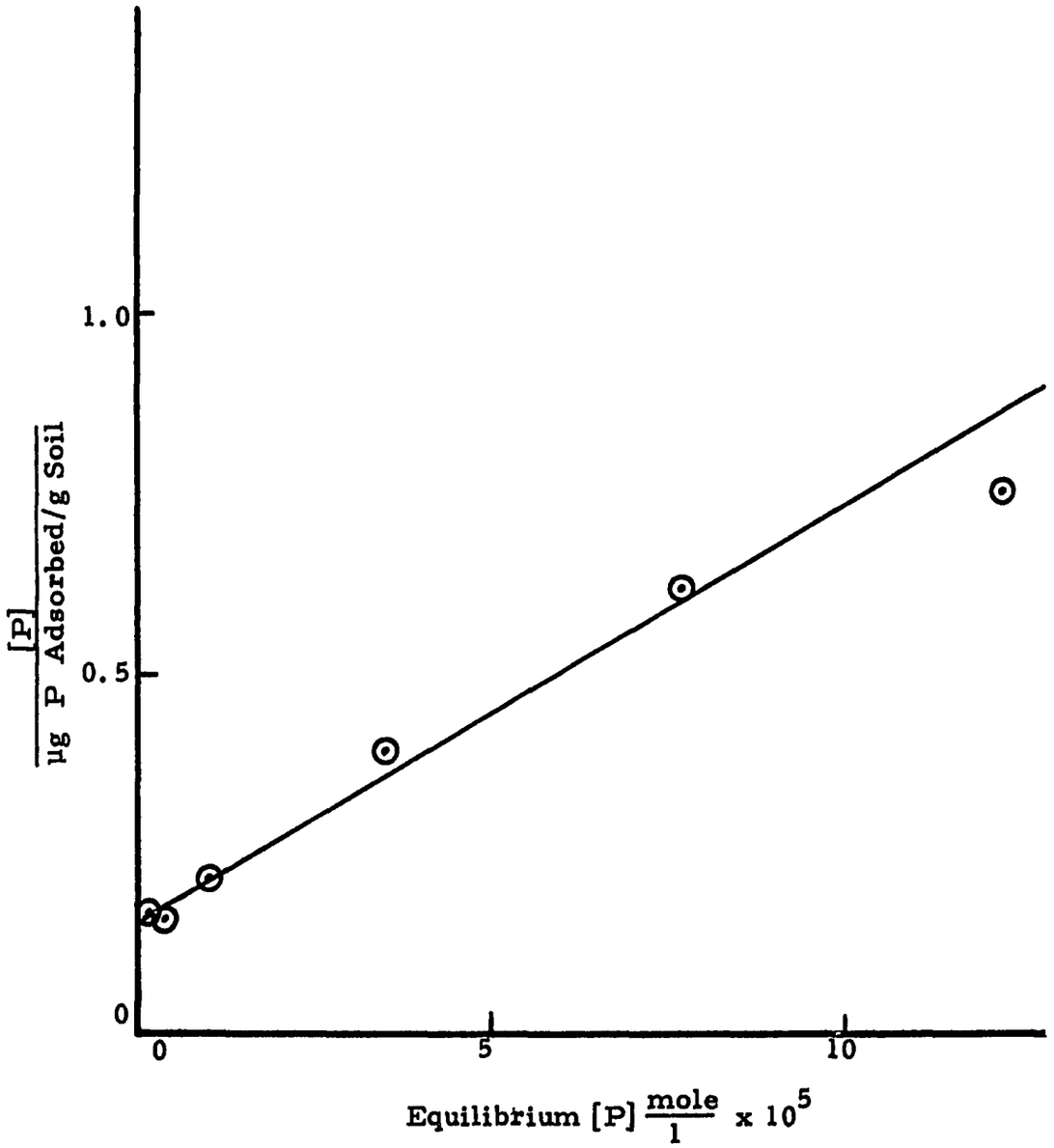


Figure 53. Langmuir Isotherm for Nibley 13-20 in. Horizon.

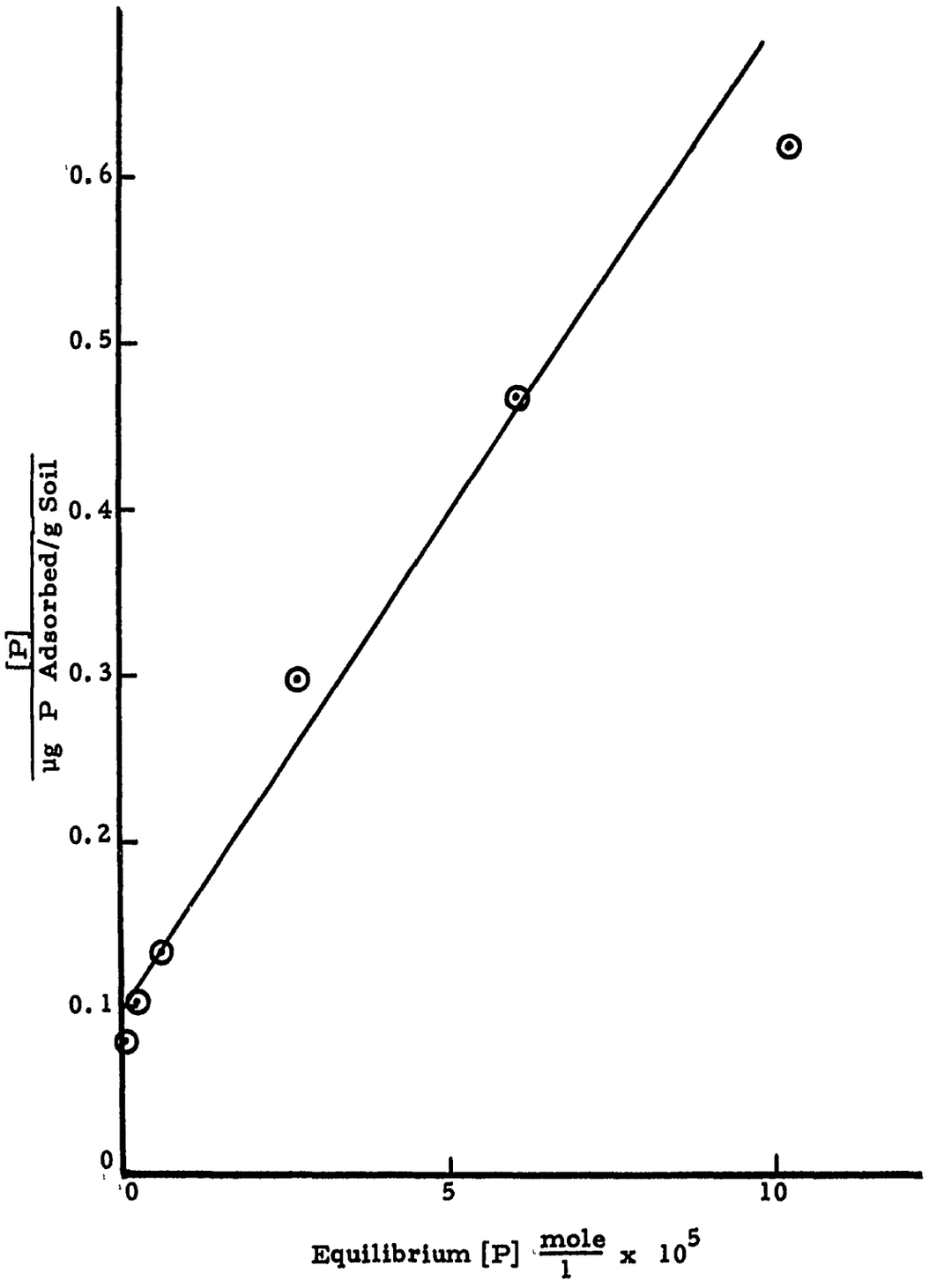


Figure 54. Langmuir Isotherm for Nibley 20-32 in. Horizon.

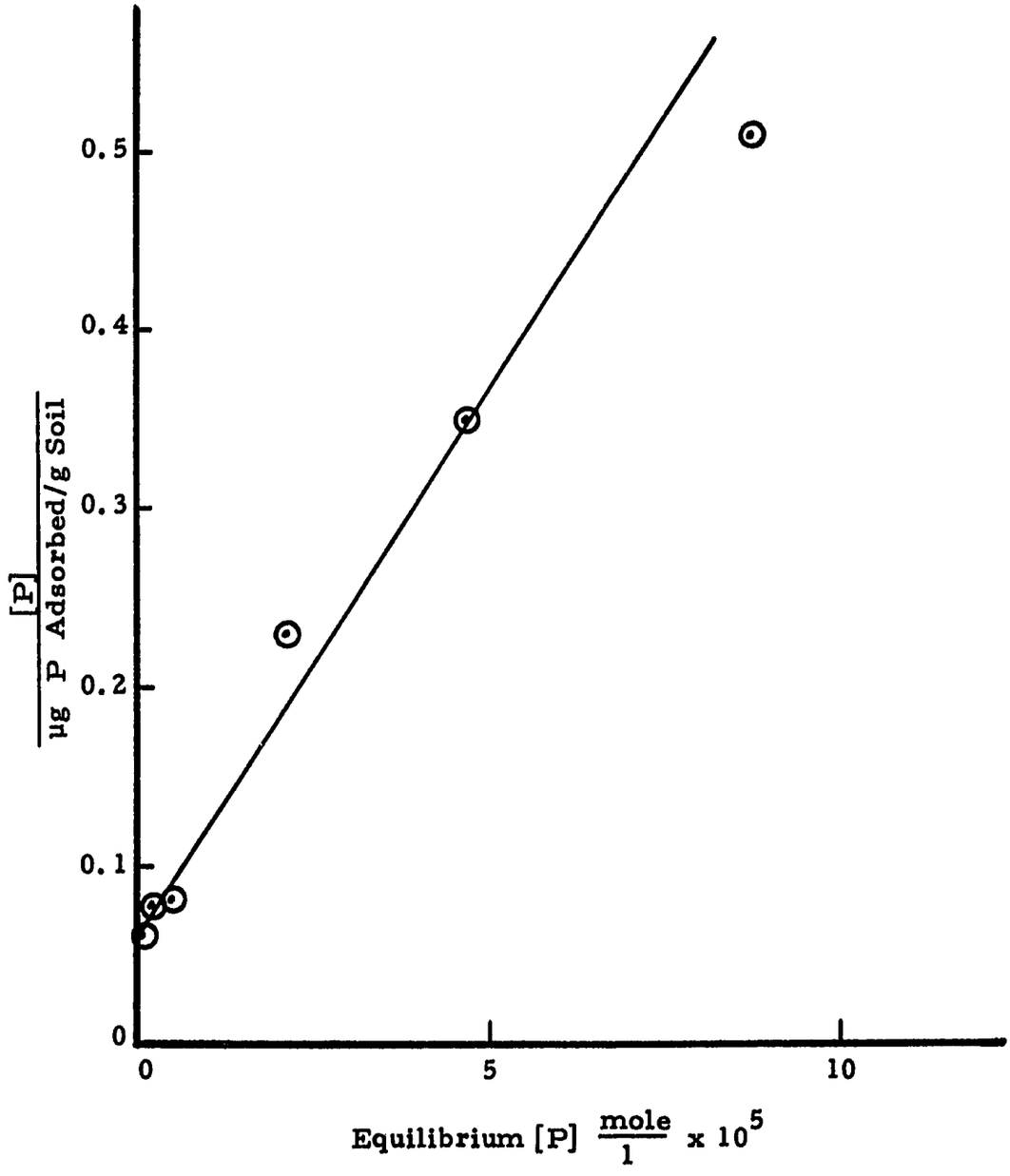


Figure 55. Langmuir Isotherm for Nibley 32-43 in. Horizon.

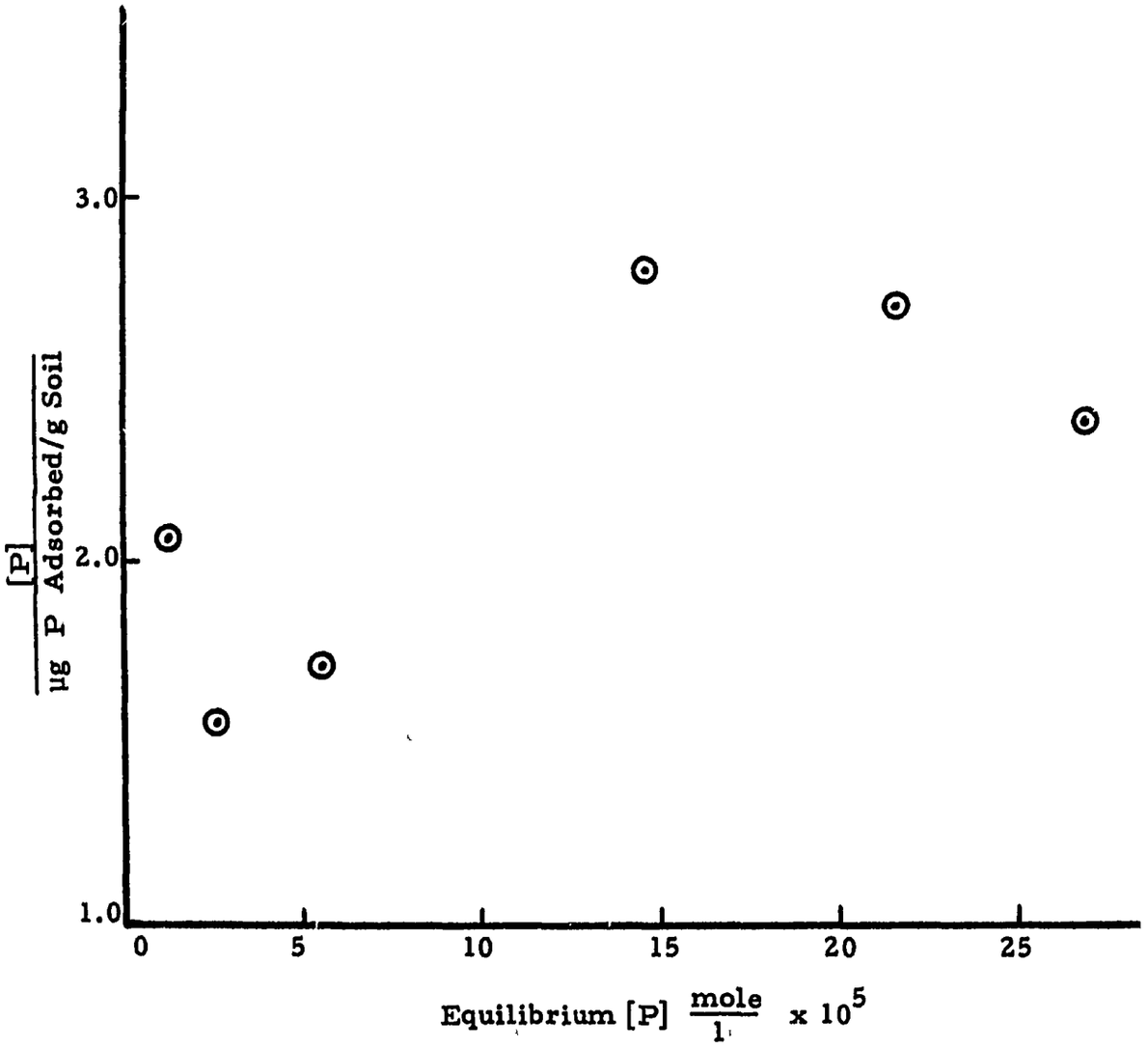


Figure 56. Langmuir Isotherm for Warm Springs 0-6 in. Horizon.

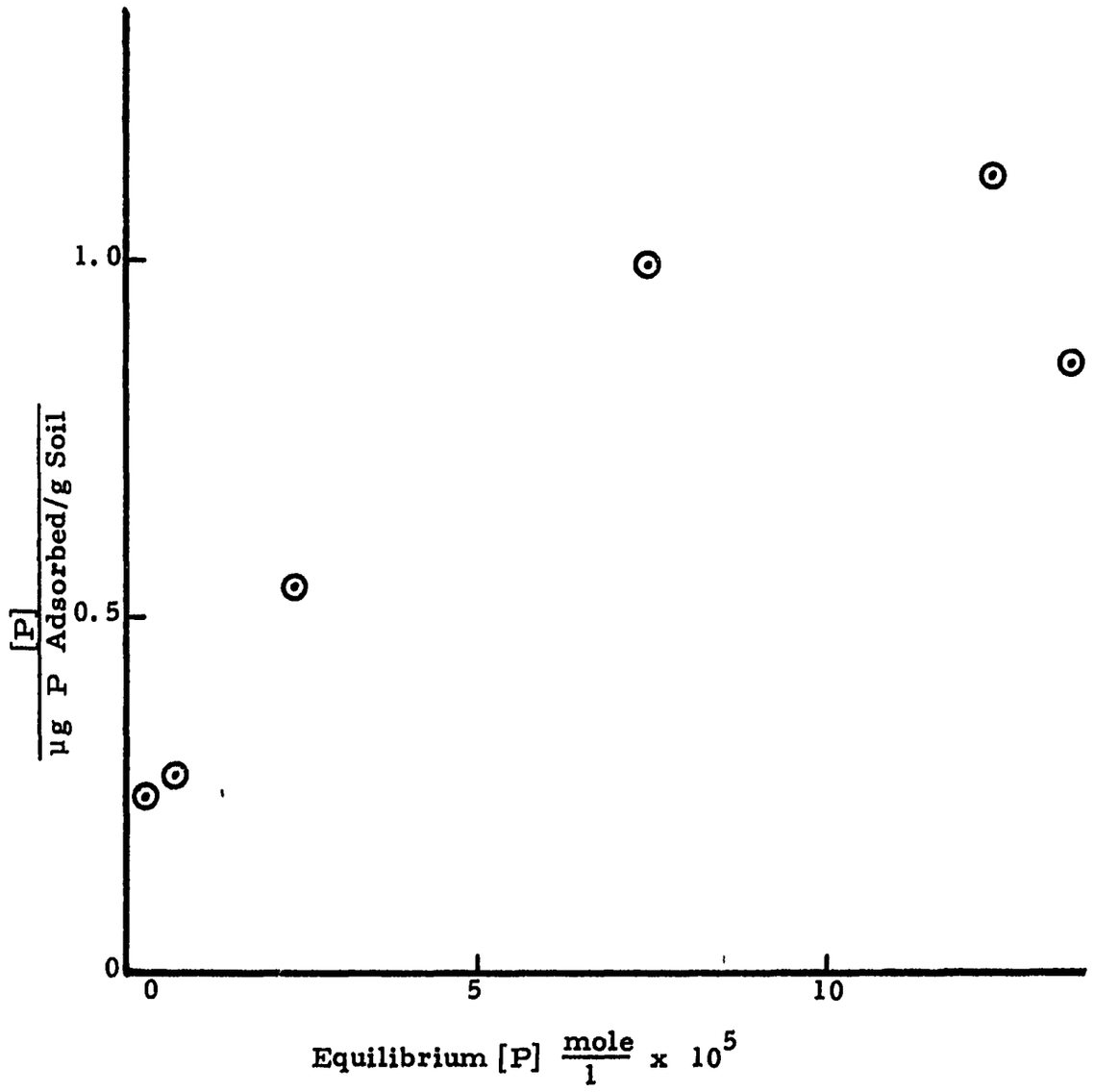


Figure 57. Langmuir Isotherm for Warm Springs 6-37 in. Horizon.

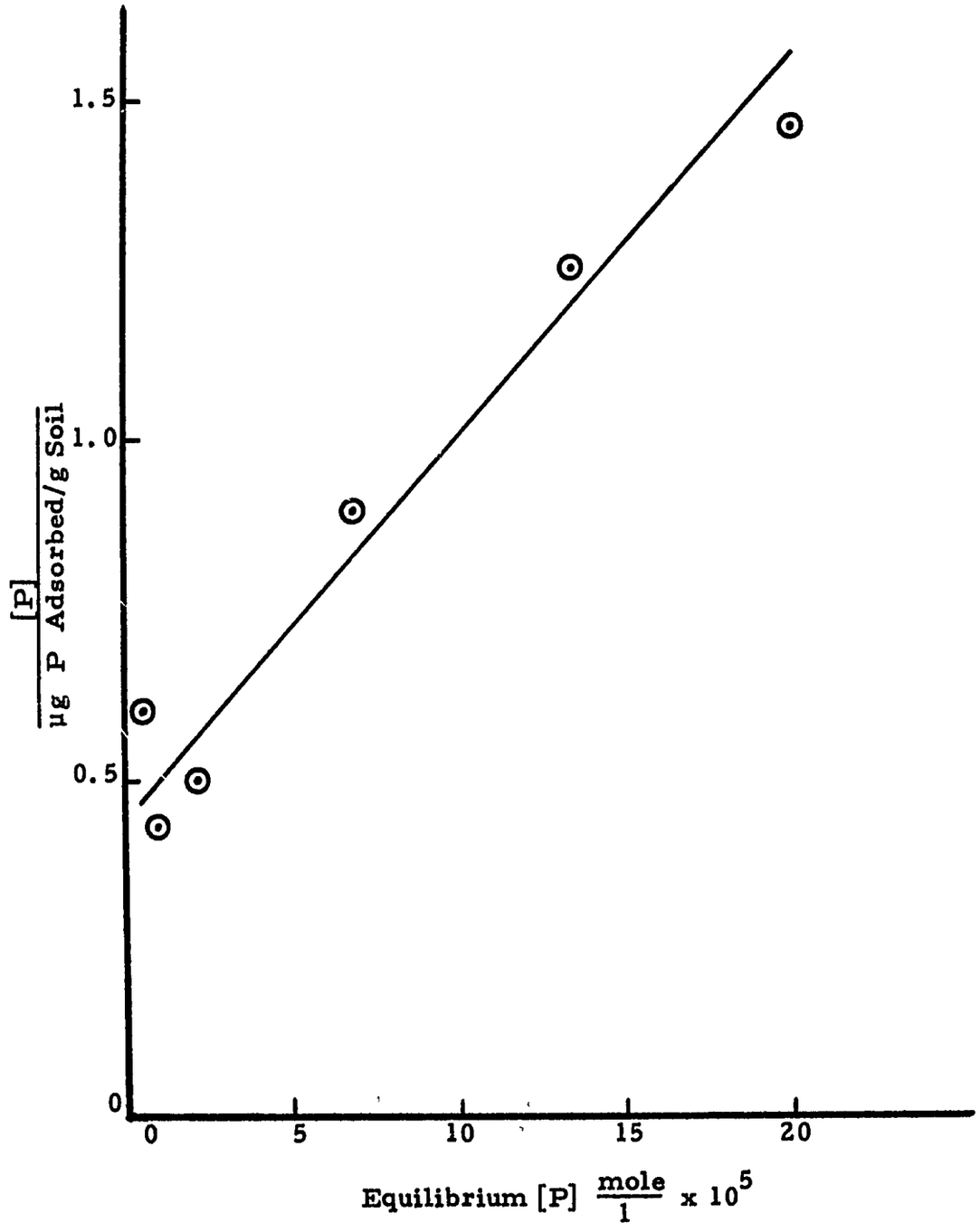


Figure 58. Langmuir Isotherm for Kilburn 0-11 in. Horizon.

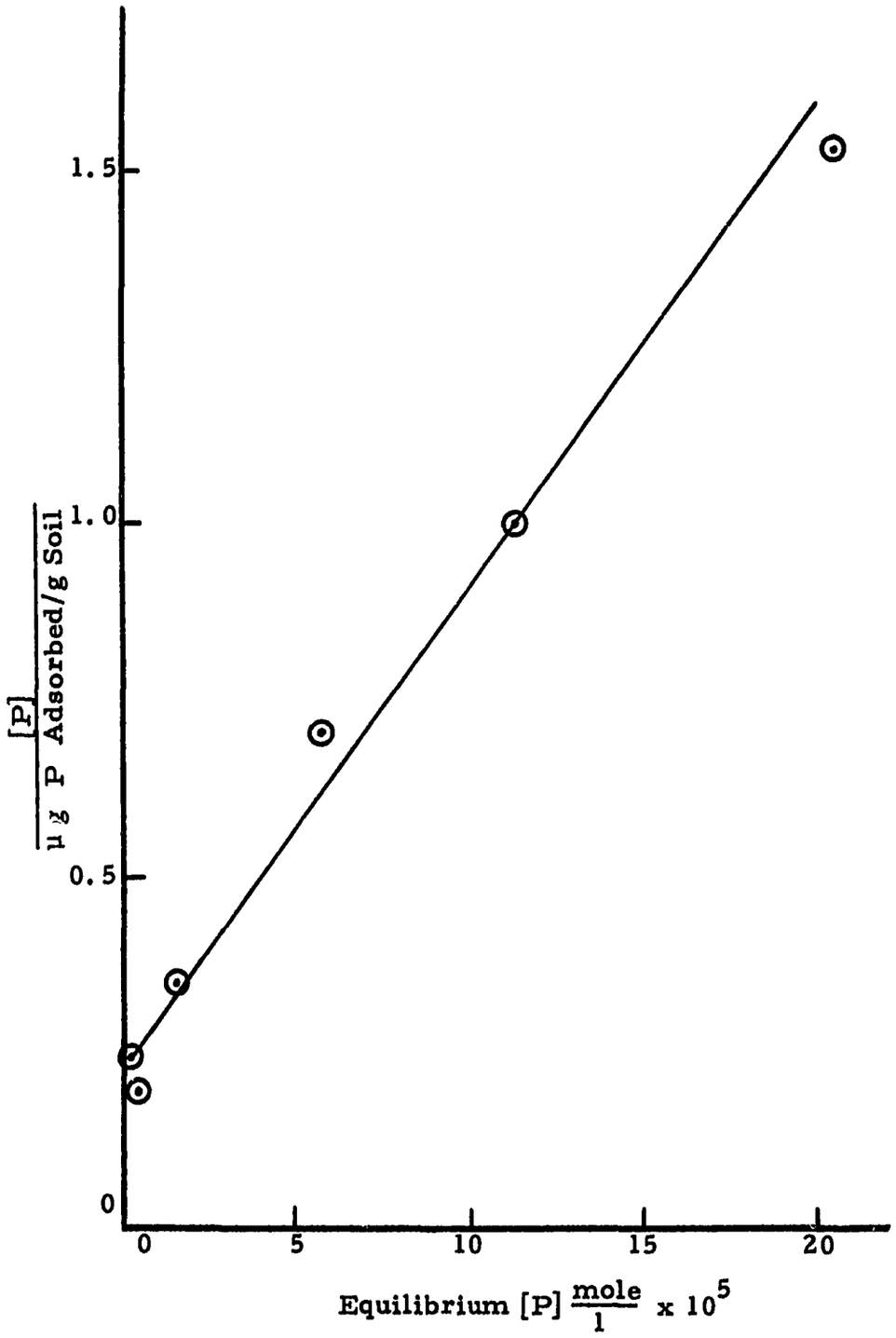


Figure 59. Langmuir Isotherm for Kilburn 11-24 in. Horizon.

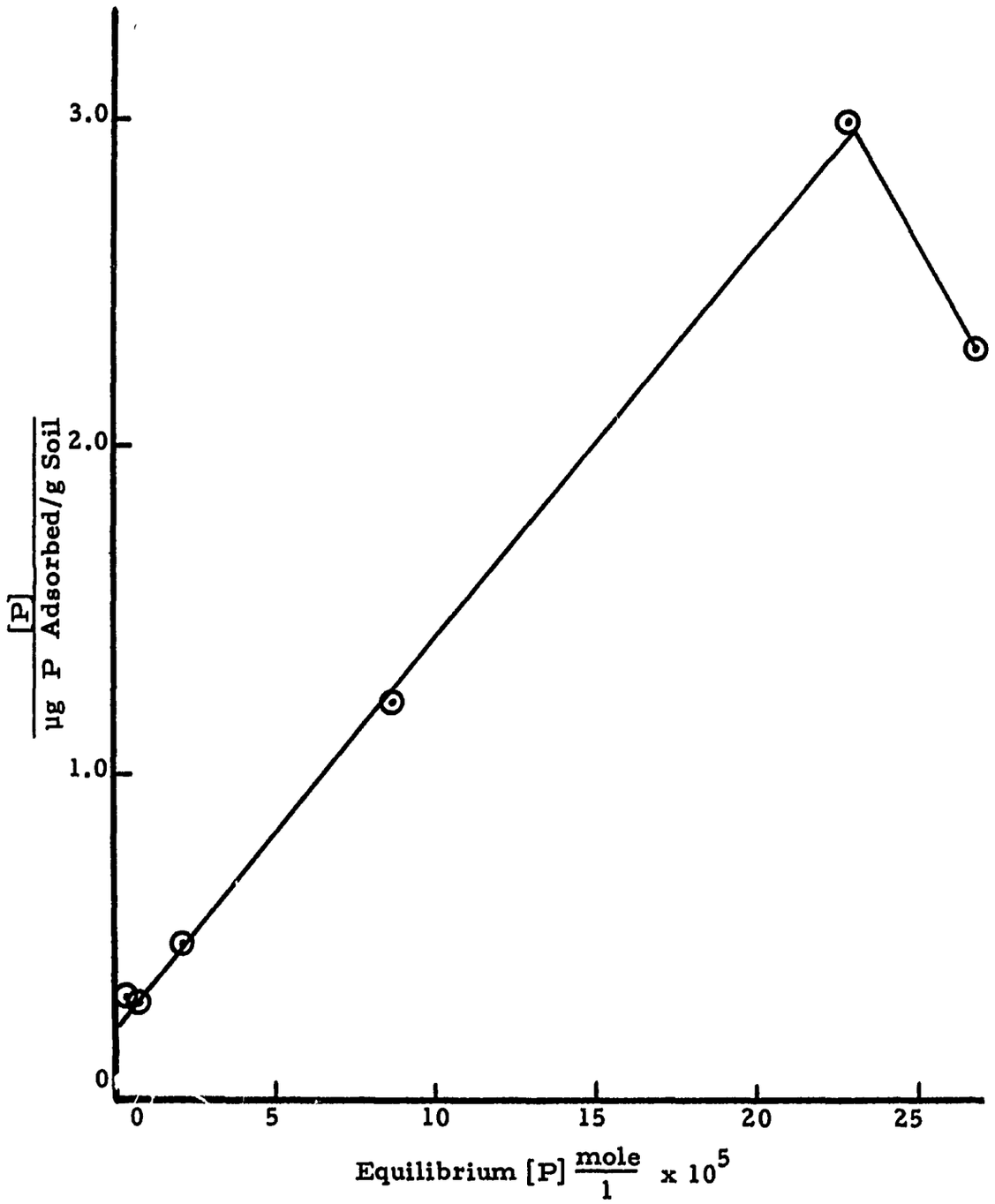


Figure 60. Langmuir Isotherm for Kilburn 24-60 in. Horizon.

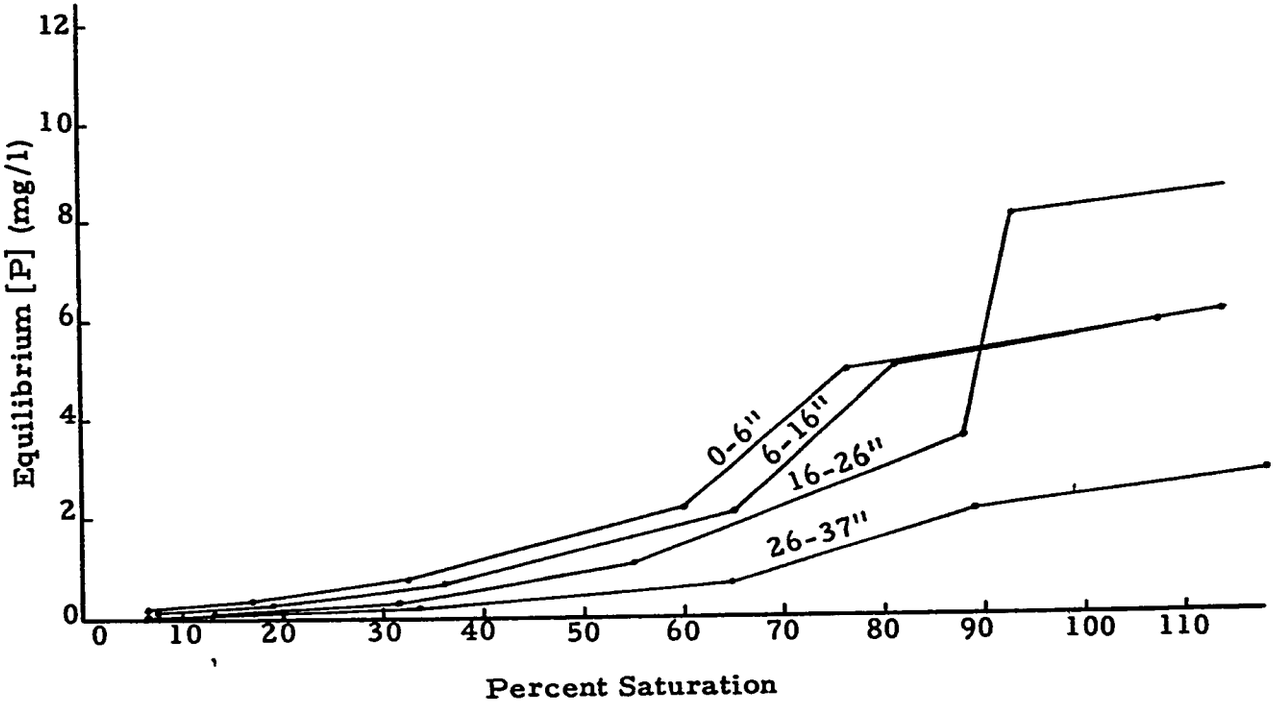


Figure 61. Equilibrium [P] versus Percent Saturation of Langmuir Adsorption Maximum for Draper Horizons.

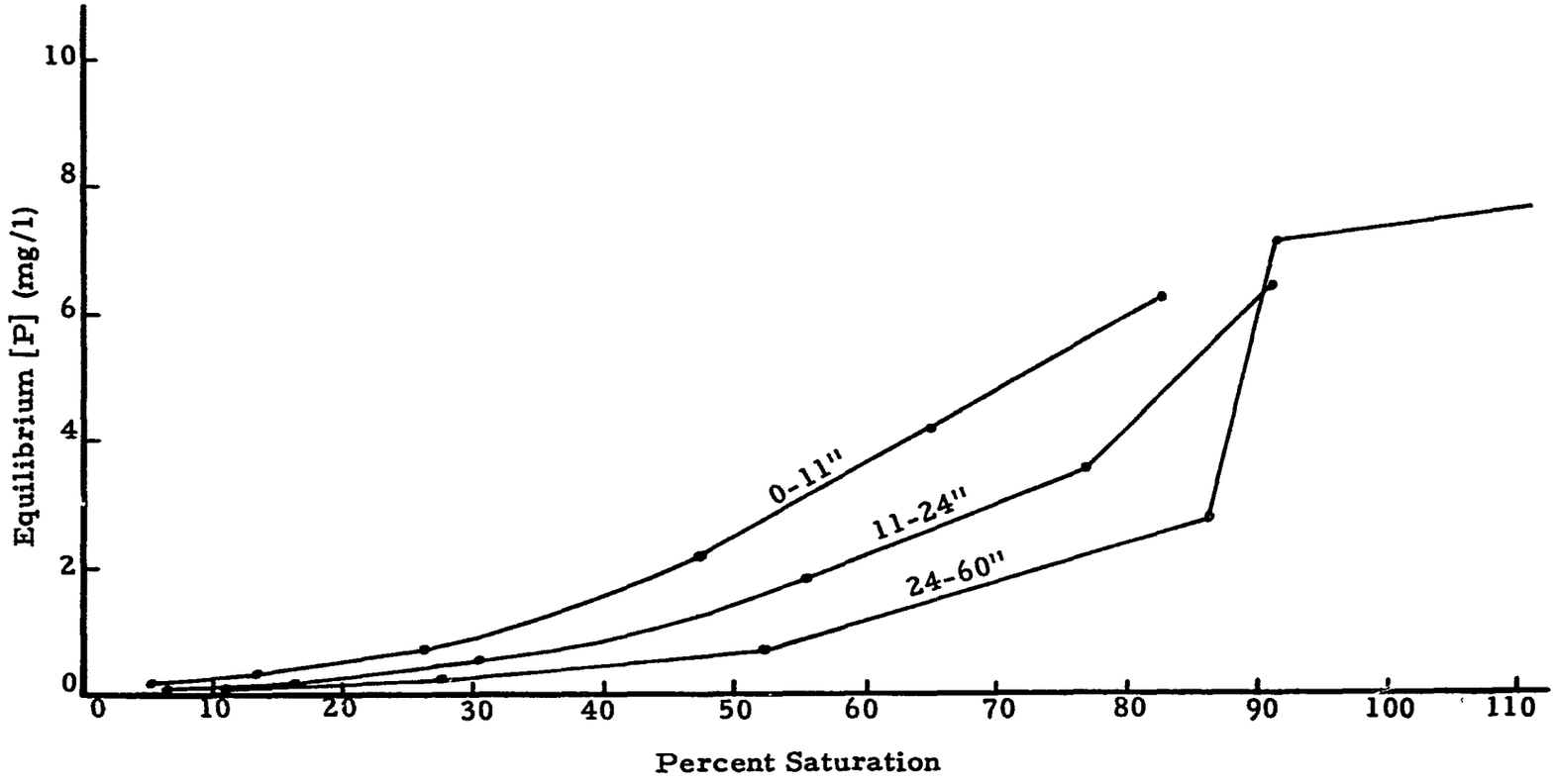


Figure 62. Equilibrium [P] versus Percent Saturation of Langmuir Adsorption Maximum for Kilburn Horizons.

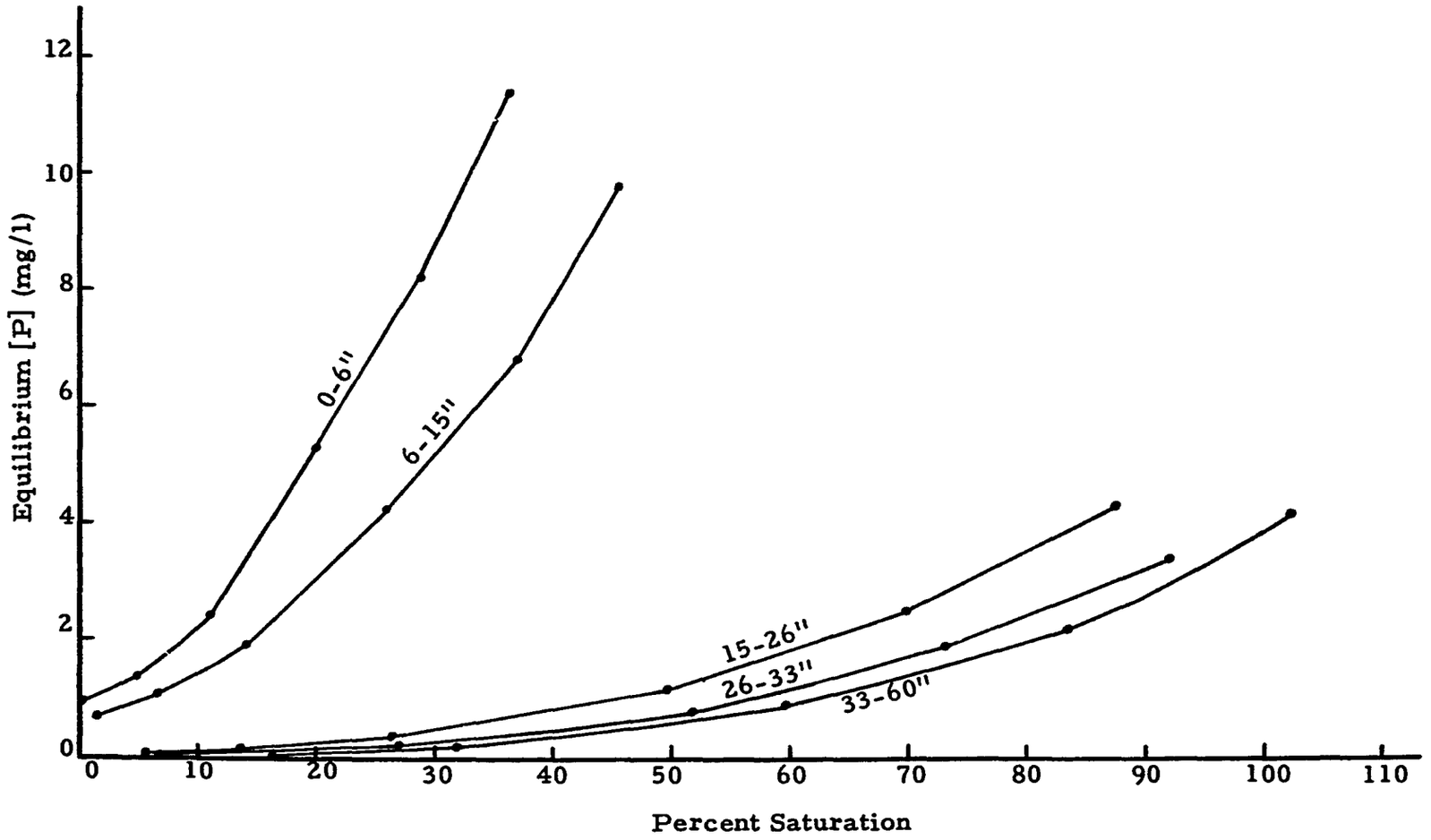


Figure 63. Equilibrium [P] versus Percent Saturation of Langmuir Adsorption Maximum for Parleys Horizons.

Appendix D

Computer Program

```
FORTRAN IV G LEVFL  18                    MAIN                D/TE = 70325          20/44/44

0001              DIMENSION BD(7),SOILT(6),N(7),DLC(7),BX(6),ICOUN(7),C1(6,100),C2(6
                 1,100)
                C
                C  J=MAIN LAYER, K=SUBLAYERS
                C
0002              COMMON J,Y,X1(7,500),K,X2(7,500),Y1(45,41),Y2(45,41),Y3(45,41),Y4(
                 145,41),Y5(45,41)
0003           73 KLAY=0
0004              LTER=0
0005              TER=0.
0006              READ(5,200,END=500)X1(1,1),WINC,(BD(J),J=1,6),(SOILT(K),K=1,6),SLT
                 1,XIMAX,LAYR,NEWSO,ITEST,INTI
0007              IF(NEWSO)73,73,71
0008           71 KLAY=KLAY+1
0009              IF(KLAY-LAYR)72,72,73
0010           72 GO TO(74,75,76,77,78),KLAY
0011           74 DO 70 I=1,45
0012              READ(5,210)(Y1(I,J),J=1,21)
0013              READ(5,210)(Y1(I,J),J=22,41)
0014           70 CONTINUE
0015              GO TO 71
0016           75 DO 70 I=1,45
0017              READ(5,210)(Y2(I,J),J=1,21)
0018              READ(5,210)(Y2(I,J),J=22,41)
0019           70 CONTINUE
0020              GO TO 71
0021           76 DO 70 I=1,45
0022              READ(5,210)(Y3(I,J),J=1,21)
0023              READ(5,210)(Y3(I,J),J=22,41)
0024           80 CONTINUE
0025              GO TO 71
0026           77 DO 81 I=1,45
0027              READ(5,210)(Y4(I,J),J=1,21)
0028              READ(5,210)(Y4(I,J),J=22,41)
0029           81 CONTINUE
0030              GO TO 71
0031           78 DO 82 I=1,45
0032              READ(5,210)(Y5(I,J),J=1,21)
0033              READ(5,210)(Y5(I,J),J=22,41)
0034           82 CONTINUE
0035           71 WRITE(6,213)ITEST
0036              WRITE(6,215)X1(1,1),WINC
0037              NN=0
0038              DO 30 K=1,6
0039              IF(K-LAYR)[illegible]
0040           [illegible] N(K)=1
0041              GO TO 30
0042           [illegible] D(K)=SOILT(K)/SLT
0043              SPL=D(K)
0044              DLC(K)=2.54*SLT
0045              NN=NN+N(K)
0046           30 CONTINUE
0047              WRITE(6,216)DLC(1)
0048              WRITE(6,217)
0049              WRITE(6,843)
0050              WRITE(6,218)
```

```
0051          DO 6 MN=1,LAYR
0052          COR=N(MN)
0053          CENT1=COR*DLC(MN)
0054          CENT=SOILT(MN)*2.54
0055        6 WRITE(6,219)MN,BD(MN),SOILT(MN),CENT,CENT1,N(MN)
0056          NMAX=0
0057          WRITE(6,525) X1MAX
0058          WRITE(6,213) ITEST
0059          DO 40 K=1,6
0060          IF(N(K)-NMAX)40,40,41
0061       41 NMAX=N(K)
0062       40 CONTINUE
0063          BD(7)=1.3
0064          DLC(7)=5.0
0065          N(7)=1
0066          ITER=0
0067          NO=N(1)
0068          K=0
0069          DO 580 J=1,6
0070          DO 580 K=1,100
0071          C1(J,K)=100000000000.
0072      580 C2(J,K)=100000000000.
0073          DO 1 J=1,6
0074          DO 1 K=1,500
0075          X2(J,K)=0.0
0076          IF(J-1)1,1,232
0077      232 X1(J,K)=0.
0078        1 CONTINUE
0079          DO 100 LM=1,7
0080      100 ICOUN(LM)=1
0081          DO 5 J=1,LAYR
0082          BX(J)=X1(1,1)*WINC/DLC(J)/BD(J)
0083          LXN=X1(1,1)/.5+1.0
0084          GO TO(120,121,122,123,124),J
0085      120 YO=Y1(45,LXN)
0086          GO TO 125
0087      121 YO=Y2(45,LXN)
0088          GO TO 125
0089      122 YO=Y3(45,LXN)
0090          GO TO 125
0091      123 YO=Y4(45,LXN)
0092          GO TO 125
0093      124 YO=Y5(45,LXN)
0094      125 IF(BX(J)-YO)126,126,127
0095      127 ICOUN(J)=1
0096          GO TO 5
0097      126 ICOUN(J)=0
0098        5 CONTINUE
0099          IF(ICOUN(1)1131,131,10
0100       10 TEP=TEP+1.0
0101          J=1
0102          K=1
0103          CALL SOIL1
0104          B=WINC*X1(1,1)/DLC(1)/BD(1)
0105          Z=Y-B
0106          IF(Z+0.1)8,9,9
```

```
0107          9 X2(J,K)=X2(J,K)+B
0108            GO TO 10
0109          8 K=K+1
0110            X2(J,K-1)=X2(J,K-1)+Y
0111            KTO=K-1
0112            KZ=K-1
0113            IF(K-N(1))560,560,561
0114        560 J=1
0115            GO TO 581
0116        561 IF(K-(N(1)+N(2)))562,562,563
0117        562 J=2
0118            GO TO 581
0119        563 IF(K-(N(1)+N(2)+N(3)))564,564,565
0120        564 J=3
0121            GO TO 581
0122        565 IF(K-(N(1)+N(2)+N(3)+N(4)))566,566,567
0123        566 J=4
0124            GO TO 581
0125        567 J=5
0126        581 B=-Z
0127            IF(LAYR-J)241,242,242
0128        241 X1(J,K)=B*BD(J)*DLC(J-1)/WINC
0129            GO TO 243
0130        242 X1(J,K)=B*BD(J)*DLC(J)/WINC
0131        243 IF(J-LAYR-1)18,50,50
0132         50 IF(X1(J,NN+1)-X1MAX)9,19,19
0133         19 JX=J-1
0134            GO TO 15
0135         18 CALL SOIL1
0136            Z=Y-B
0137            IF(Z+0.1)14,9,9
0138         14 IF(NO-K)15,15,8
0139         15 IJUD=J+1
0140            X2(J,K)=X2(J,K)+Y
0141            KBO=K
0142            WPAS=TEP*WINC
0143            JBO=J
0144            KJN=0
0145            J=1
0146            NNN=N(1)
0147            DO 570 K=1,NNN
0148            C1(J,K)=X1(J,K)
0149        570 C2(J,K)=X2(J,K)
0150         21 DO 16 J=2,6
0151            NX=N(J)
0152            KON=KON+N(J-1)
0153            IF(J-LAYR)303,303,302
0154        303 DO 16 K=1,NX
0155            C1(J,K)=X1(J,KON+K)
0156         16 C2(J,K)=X2(J,KON+K)
0157        302 LTEP=LTER+NMAX+10
0158            IF(JBO-1)96,96,301
0159        301 IF(57-LTER)95,96,96
0160         95 WRITE(6,213)ITEST
0161            LTER=NMAX+10
0162         96 IF(LAYR-JBO)97,305,305
```

```
OPTRAN IV G LEVEL  18                    MAIN                    DATE = 70325          20/44/44

0163          97 IF(X1(JBO,NN+1)-X1MAX)96,98,98
0164          98 WRITE(6,205)X1(JBO,NN+1),JX,WPAS
0165             GO TO 99
0166         305 WRITE(6,201)JBO,IDUD,WPAS
0167          99 WRITE(6,202)
0168             WRITE(6,203)
0169             WRITE(6,225)
0170             DO 17 K=1,NMAX
0171          17 WRITE(6,204)K,(C2(J,K),J=1,6),(C1(J,K),J=1,6)
0172             WRITE(6,206)
0173             IF(NO-NN)22,22,23
0174          22 J=JBO
0175             IF(ICOUN(IDUD))131,131,130
0176         131 WRITE(6,214)IDUD
0177             GO TO 23
0178         130 K=KBO
0179             X2(J,K)=X2(J,K)-Y
0180             NO=NO+N(J+1)
0181             GO TO 8
0182         200 FORMAT(F5.2,F4.1,6F3.2,6F4.2,F5.3,F5.2,2I1,2I4)
0183         201 FORMAT(1H ,36HLOADING AND CONCENTRATION WHEN LAYER,I2,29H FIRST PA
                1SSES PHOS ONTO LAYER,I2,31H----QUANTITY OF WATER ADDED WAS,F10.2,1
                12H MILLILITERS,/)
0184         202 FORMAT(1H ,9X,45H- - - - - - - - - - L A Y E R - - - - - - - - - -,12X
                1,49H- - - - - - - - - - L A Y E P - - - - - - - - - - -)
0185         203 FORMAT(1H ,55H SUBLAYER      1        2        3        4        5
                1  6,16X,41H1        2        3        4        5        6)
0186         204 FORMAT(1H ,I5,4X,6F8.2,9X,6F8.3)
0187         225 FORMAT(1H ,25X,13HL O A D I N G,41X,25HC O N C E N T R A T I O N,/
                1)
0188         205 FORMAT(1H ,31HLOADING AND CONCENTRATION WHEN ,F5.2,26H PHOS PASSED
                1 THROUGH LAYER,I2,31H----QUANTITY OF WATER ADDED WAS,F10.2,13H MIL
                2LILITERS,/)
0189         206 FORMAT(1H ,////)
0190         210 FORMAT(7X,21F3.0)
0191         211 FORMAT(1H ,21F5.0)
0192         213 FORMAT(1H1,12HTEST NUMBER: ,I4,//)
0193         214 FORMAT(1H ,34HSYSTEM IS NOT CONVERGENT IN LAYER ,I2)
0194         215 FORMAT(1H ,F5.2,18H PPM PHOS ADDED IN,F7.2,22H MILLILITER INCREMEN
                1TS,//)
0195         216 FORMAT(1H ,18HSUBLAYER THICKNESS,F6.2,12H CENTIMETERS,//)
0196         217 FORMAT(1H ,57HLAYER   BULK DENSITY          THICKNESS          SUBL
                 1AYERS)
0197         218 FORMAT(1H ,10X,35H(GM/CC)     (INCHES) (CENT)  (CENT),/)
0198         219 FORMAT(1H ,1I3,2F13.2,2F8.2,6X,I3,/)
0199         220 FORMAT(1H1)
0200         525 FORMAT(1HC,58HMAXIMUM CONCENTRATION ALLOWED TO PASS THROUGH LAST L
                1AYER: ,F5.2)
0201         833 FORMAT(1H ,27X,19HACTUAL     COMPUTED)
0202         500 WRITE(6,220)
0203             STOP
0204             END
```

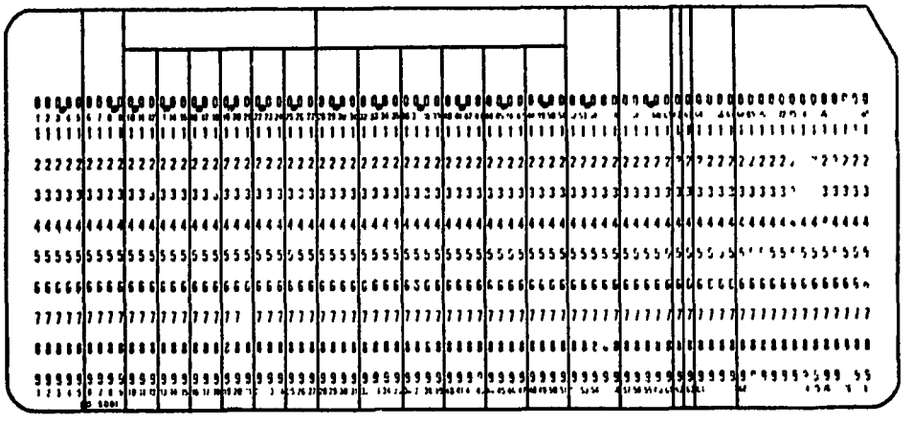
```
FORTRAN IV G LEVEL  18                SOIL1                DATE = 70325          20/44/44

0001              SUBROUTINE SOIL1
0002              COMMON J,Y,X1(7,500),K,X2(7,500),Y1(45,41),Y2(45,41),Y3(45,41),Y4(
                 145,41),Y5(45,41)
0003              NX11=X1(J,K)/.5+1.0
0004              NX12=NX11+1
0005              NX21=X2(J,K)/50.+1.0
0006              NX22=NX21+1
0007              IF(NX22-46)15,16,16
0008           16 NX22=45
0009              NX21=45
0010           15 NOO=X1(J,K)/.5
0011              XB=NOO
0012              XX=XB/2.
0013              X12=X1(J,K)-XX
0014              GO TO (1,2,3,4,5),J
0015            1 YY1=Y1(NX21,NX12)
0016              YY2=Y1(NX21,NX11)
0017              YY3=Y1(NX22,NX12)
0018              YY4=Y1(NX22,NX11)
0019              GO TO 10
0020            2 YY1=Y2(NX21,NX12)
0021              YY2=Y2(NX21,NX11)
0022              YY3=Y2(NX22,NX12)
0023              YY4=Y2(NX22,NX11)
0024              GO TO 10
0025            3 YY1=Y3(NX21,NX12)
0026              YY2=Y3(NX21,NX11)
0027              YY3=Y3(NX22,NX12)
0028              YY4=Y3(NX22,NX11)
0029              GO TO 10
0030            4 YY1=Y4(NX21,NX12)
0031              YY2=Y4(NX21,NX11)
0032              YY3=Y4(NX22,NX12)
0033              YY4=Y4(NX22,NX11)
0034              GO TO 10
0035            5 YY1=Y5(NX21,NX12)
0036              YY2=Y5(NX21,NX11)
0037              YY3=Y5(NX22,NX12)
0038              YY4=Y5(NX22,NX11)
0039           10 BNT1=(YY1-YY2)*X12/0.5+YY2
0040              BNT2=(YY3-YY4)*X12/0.5+YY4
0041              X3=X2(J,K)/50.
0042              LX3=X3
0043              XX3=LX3
0044              CFX3=X3-XX3
0045              Y=(BNT2-BNT1)*CFX3+BNT1
0046              RETURN
0047              END
```

Appendix E

Example Problem Showing Computer Input and Output

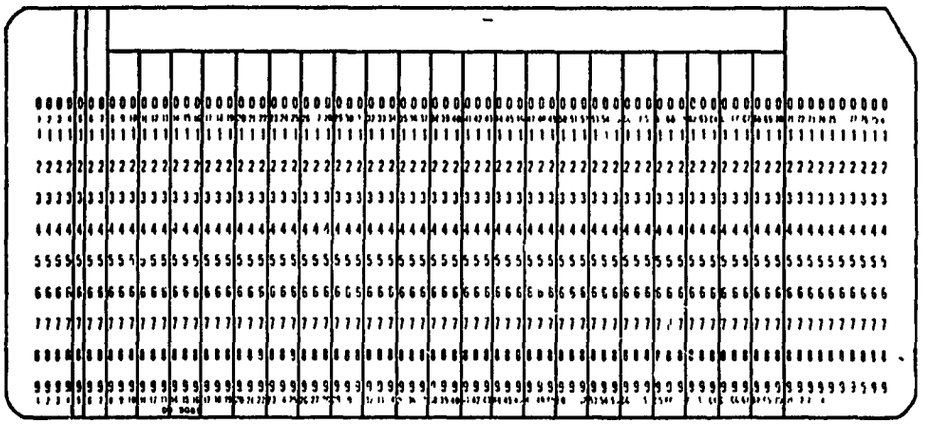
Sample Control Card



A separate control card must be included for each desired change in the initial conditions of the phosphorus water application. The items to be punched on each card are as follows:

Columns	Description
(1-5)	Input concentration, in mg/l as P
(6-9)	Water increment (WINC) in milliliters
(10-12)	Bulk density of main layer #1, in g/cm^3
(13-15)	Bulk density of main layer #2, etc.
(28-31)	Thickness of main layer #1, in inches
(32-35)	Thickness of main layer #2, etc.
(52-56)	Sub-layer thickness, in inches
(57-61)	Limit concentration in outflow, mg/l as P
(62)	Number of main layers in profile
(63)	Punch "1" if introducing new soil, "0" if same soil
(64-67)	Test Number

Sample Data Card



Data from the repeated adsorption tests were punched onto cards as follows:

Columns	Description
(1-4)	P loading (x_2) values, in μg P/g soil.
(5)	Code "1" or "2", for 1st or 2nd card, since data for each loading (x_2) value was continued on a 2nd card.
(6-7)	Main layer identification. If data was for 0-7" horizon, "0" punched, if for 7-13", "7" punched, etc.
(8-10)	Adsorption (y) value in μg P/g soil for initial concentration (x_1) value = 0 mg/l as P.
(11-13)	Adsorption (y) value in μg P/g soil for initial concentration (x_1) value = 0.5 mg/l as P.
(14-16)	y value for x_1 = 1.0 mg/l as P, etc.

TEST NUMBER: 11

15.00 PPM PHOS ADDED IN 100.00 MILLILITER INCREMENTS

SUBLAYER THICKNESS 2.54 CENTIMETERS

LAYER	BULK DENSITY (GM/CC)	THICKNESS ACTUAL (INCHES)	THICKNESS ACTUAL (CENT)	THICKNESS COMPUTED (CENT)	SUBLAYERS
1	1.51	11.00	27.94	27.94	11
2	1.51	13.00	33.02	33.02	13
3	1.51	36.00	91.44	91.44	36

MAXIMUM CONCENTRATION ALLOWED TO PASS THROUGH LAST LAYER: 5.00

TEST NUMBER: 11

LOADING AND CONCENTRATION WHEN LAYER 1 FIRST PASSES PHOS ONTO LAYER 2----QUANTITY OF WATER ADDED WAS 100.00 MILLILITERS

SUBLAYER	LAYER 1	LAYER 2	LAYER 3	LAYER 4	LAYER 5	LAYER 6	LAYER 1	LAYER 2	LAYER 3	LAYER 4	LAYER 5	LAYER 6
	LOADING						CONCENTRATION					
1	107.00	0.0	0.0	**********			15.000	0.0	0.0	**********		
2	83.38	0.0	0.0	**********			10.896	0.0	0.0	**********		
3	63.19	0.0	0.0	**********			7.698	0.0	0.0	**********		
4	45.20	0.0	0.0	**********			5.275	0.0	0.0	**********		
5	31.33	0.0	0.0	**********			3.541	0.0	0.0	**********		
6	20.72	0.0	0.0	**********			2.340	0.0	0.0	**********		
7	13.45	0.0	0.0	**********			1.545	0.0	0.0	**********		
8	8.29	0.0	0.0	**********			1.029	0.0	0.0	**********		
9	5.69	0.0	0.0	**********			0.711	0.0	0.0	**********		
10	3.94	0.0	0.0	**********			0.493	0.0	0.0	**********		
11	2.73	0.0	0.0	**********			0.342	0.0	0.0	**********		
12	********	0.0	0.0	**********			********	0.0	0.0	**********		
13	********	0.0	0.0	**********			********	0.0	0.0	**********		
14	**********		0.0	**********			**********		0.0	**********		
15	**********		0.0	**********			**********		0.0	**********		
16	**********		0.0	**********			**********		0.0	**********		
17	**********		0.0	**********			**********		0.0	**********		
18	**********		0.0	**********			**********		0.0	**********		
19	**********		0.0	**********			**********		0.0	**********		
20	**********		0.0	**********			**********		0.0	**********		
21	**********		0.0	**********			**********		0.0	**********		
22	**********		0.0	**********			**********		0.0	**********		
23	**********		0.0	**********			**********		0.0	**********		
24	**********		0.0	**********			**********		0.0	**********		
25	**********		0.0	**********			**********		0.0	**********		
26	**********		0.0	**********			**********		0.0	**********		
27	**********		0.0	**********			**********		0.0	**********		
28	**********		0.0	**********			**********		0.0	**********		
29	**********		0.0	**********			**********		0.0	**********		
30	**********		0.0	**********			**********		0.0	**********		
31	**********		0.0	**********			**********		0.0	**********		
32	**********		0.0	**********			**********		0.0	**********		
33	**********		0.0	**********			**********		0.0	**********		
34	**********		0.0	**********			**********		0.0	**********		
35	**********		0.0	**********			**********		0.0	**********		
36	**********		0.0	**********			**********		0.0	**********		

TEST NUMBER: 11

LOADING AND CONCENTRATION WHEN LAYER 2 FIRST PASSES PHOS ONTO LAYER 3----QUANTITY OF WATER ADDED WAS 400.00 MILLILITERS

SUBLAYER	LAYER 1	LAYER 2	LAYER 3	LOADING	LAYER 1	LAYER 2	LAYER 3	CONCENTRATION
1	231.08	34.44	0.0	**********	15.000	1.870	0.0	**********
2	208.91	22.70	0.0	**********	13.811	1.218	0.0	**********
3	190.45	14.31	0.0	**********	12.623	0.766	0.0	**********
4	171.39	8.98	0.0	**********	11.409	0.481	0.0	**********
5	152.60	5.60	0.0	**********	10.115	0.300	0.0	**********
6	131.84	3.48	0.0	**********	8.828	0.186	0.0	**********
7	113.56	2.15	0.0	**********	7.578	0.115	0.0	**********
8	94.99	1.33	0.0	**********	6.269	0.071	0.0	**********
9	75.51	0.90	0.0	**********	4.920	0.044	0.0	**********
10	57.41	0.48	0.0	**********	3.690	0.027	0.0	**********
11	41.51	0.36	0.0	**********	2.663	0.017	0.0	**********
12	********	0.24	0.0	**********	********	0.010	0.0	**********
13	********	0.06	0.0	**********	********	0.006	0.0	**********
14	**********	**********	0.0	**********	**********	**********	0.0	**********
15	**********	**********	0.0	**********	**********	**********	0.0	**********
16	**********	**********	0.0	**********	**********	**********	0.0	**********
17	**********	**********	0.0	**********	**********	**********	0.0	**********
18	**********	**********	0.0	**********	**********	**********	0.0	**********
19	**********	**********	0.0	**********	**********	**********	0.0	**********
20	**********	**********	0.0	**********	**********	**********	0.0	**********
21	**********	**********	0.0	**********	**********	**********	0.0	**********
22	**********	**********	0.0	**********	**********	**********	0.0	**********
23	**********	**********	0.0	**********	**********	**********	0.0	**********
24	**********	**********	0.0	**********	**********	**********	0.0	**********
25	**********	**********	0.0	**********	**********	**********	0.0	**********
26	**********	**********	0.0	**********	**********	**********	0.0	**********
27	**********	**********	0.0	**********	**********	**********	0.0	**********
28	**********	**********	0.0	**********	**********	**********	0.0	**********
29	**********	**********	0.0	**********	**********	**********	0.0	**********
30	**********	**********	0.0	**********	**********	**********	0.0	**********
31	**********	**********	0.0	**********	**********	**********	0.0	**********
32	**********	**********	0.0	**********	**********	**********	0.0	**********
33	**********	**********	0.0	**********	**********	**********	0.0	**********
34	**********	**********	0.0	**********	**********	**********	0.0	**********
35	**********	**********	0.0	**********	**********	**********	0.0	**********
36	**********	**********	0.0	**********	**********	**********	0.0	**********

TEST NUMBER: 11

LOADING AND CONCENTRATION WHEN LAYER 3 FIRST PASSES PHOS CNTC LAYER 4----QUANTITY OF WATER ADDED WAS 3200.00 MILLILITERS

SUBLAYER	LAYER 1	2	3	4	5	6	LAYER 1	2	3	4	5	6
	LOADING						CONCENTRATION					
1	343.45	399.74	245.42				15.000	14.561	13.156			
2	340.42	399.21	244.11				14.978	14.557	13.130			
3	336.75	397.76	242.47				14.948	14.543	13.047			
4	332.42	394.22	240.30				14.908	14.504	13.053			
5	327.69	386.80	237.51				14.861	14.409	12.994			
6	322.73	375.56	234.33				14.809	14.231	12.916			
7	317.90	365.43	230.09				14.754	14.023	12.813			
8	313.60	359.65	225.02				14.702	13.892	12.673			
9	309.94	355.37	218.45				14.656	13.788	12.482			
10	307.01	352.20	211.59				14.616	13.705	12.213			
11	304.81	349.89	200.86				14.585	13.643	11.838			
12	********	346.88	192.03				********	13.555	11.402			
13	********	342.24	181.43				********	13.412	10.920			
14	**********	*******	171.78				**********		10.382			
15	**********		161.79				**********		9.787			
16	**********		151.31				**********		9.123			
17	**********		139.14				**********		8.346			
18	**********		124.99				**********		7.457			
19	**********		110.28				**********		6.502			
20	**********		93.85				**********		5.410			
21	**********		75.49				**********		4.279			
22	**********		58.21				**********		3.292			
23	**********		44.39				**********		2.464			
24	**********		31.99				**********		1.775			
25	**********		22.70				**********		1.245			
26	**********		15.50				**********		0.848			
27	**********		10.46				**********		0.567			
28	**********		6.76				**********		0.363			
29	**********		4.15				**********		0.227			
30	**********		2.65				**********		0.141			
31	**********		1.66				**********		0.088			
32	**********		1.04				**********		0.054			
33	**********		0.55				**********		0.034			
34	**********		0.41				**********		0.021			
35	**********		0.28				**********		0.013			
36	**********		0.08				**********		0.008			

TEST NUMBER: 11

LOADING AND CONCENTRATION WHEN 6.21 PHOS PASSED THROUGH LAYER 3----QUANTITY OF WATER ADDED WAS 4400.00 MILLILITERS,

SUBLAYER	LAYER 1	LAYER 2	LAYER 3	LAYER 1	LAYER 2	LAYER 3
	LOADING			CONCENTRATION		
1	347.59	400.00	248.4*	15.000	14.652	13.900*
2	346.38	399.99	248.04*	14.992	14.652	13.904*
3	344.79	399.98	247.52*	14.980	14.652	13.899*
4	342.71	399.95	246.86*	14.963	14.652	13.892*
5	340.10	399.87	246.05*	14.941	14.651	13.883*
6	336.87	399.68	245.19*	14.912	14.648	13.872*
7	333.06	399.27	244.11*	14.877	14.642	13.858*
8	328.82	398.37	242.96*	14.835	14.628	13.841*
9	324.31	396.50	241.64*	14.789	14.597	13.819*
10	319.80	392.80	240.61*	14.741	14.533	13.794*
11	315.59	386.14	239.16*	14.695	14.410	13.764*
12	********	377.14	238.43*	********	14.223	13.728*
13	********	368.97	237.41*	********	14.033	13.685*
14	**********		236.91*	**********		13.644*
15	**********		236.70*	**********		13.595*
16	**********		236.44*	**********		13.543*
17	**********		236.74*	**********		13.488*
18	**********		236.33*	**********		13.430*
19	**********		236.27*	**********		13.369*
20	**********		235.53*	**********		13.303*
21	**********		234.06*	**********		13.230*
22	**********		232.68*	**********		13.146*
23	**********		230.10*	**********		13.048*
24	**********		226.93*	**********		12.928*
25	**********		224.01*	**********		12.777*
26	**********		219.89*	**********		12.590*
27	**********		214.79*	**********		12.349*
28	**********		207.99*	**********		12.027*
29	**********		200.35*	**********		11.612*
30	**********		191.82*	**********		11.146*
31	**********		182.53*	**********		10.627*
32	**********		173.14*	**********		10.044*
33	**********		162.25*	**********		9.419*
34	**********		151.37*	**********		8.761*
35	**********		139.15*	**********		7.989*
36	**********		124.78*	**********		7.135*

VITA

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Personal Data: Born at Rochester, Indiana, November 26, 1942, son of Edward D. and Dora Rowe Shewman; married Helen L. Scott August 29, 1964; two children-Amy Louise and Audrey Lyn.

Education: Attended elementary school in Akron, Indiana, graduated from Akron High School in 1960, received the Bachelor of Science degree in civil engineering from Purdue University in 1964; received the Master of Science degree in civil engineering (engineering geology major) from Purdue University in 1966, did graduate work for the Ph.D. degree at Utah State University from 1967 - 1971.

Professional Experience: 1970 to present, research fellow with Agricultural and Irrigation Engineering Department, Utah State University; 1967-1970, National Science Foundation Trainee, Utah State University; 1964-1967, graduate teaching assistant, Engineering Geology Department, Purdue University. Joined the civil engineering faculty at North Dakota State University, Fargo, North Dakota, in 1971.