Utilization of wastewater as phosphorus fertilizer & modeling sorption to soil as mediation of P loss

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Geochemistry (Spring 2025)

Phosphorous

- Plant essential nutrient
- PO_4^{3-} is plant available
  - Comes mostly from mineral sources in inorganic forms
  - Availability influenced by mineral solubility
  - Can leave soil through leaching or erosion
- Usually supplemented by fertilizer
  - Rock phosphate (Ca10(PO4)6(X)2)
    - Fluorapatite

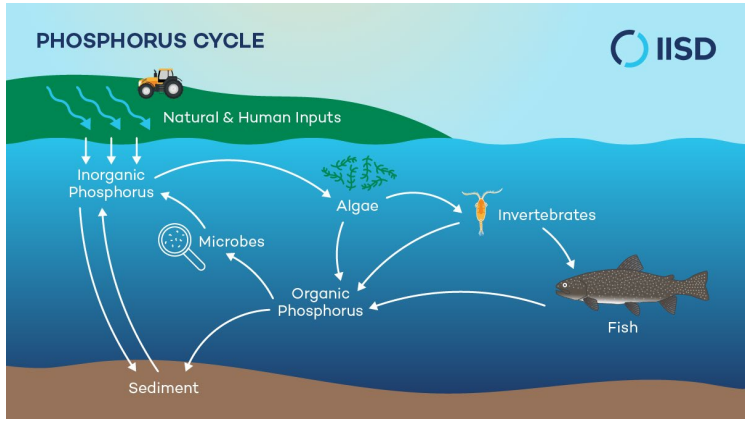


Photo courtesy of IISD

Photo courtesy of MinDat

Factors impacting P availability

- **pH**
  - More soluble around neutral pH
    - Binds with Ca at high pH
    - Binds with Al and Fe
- **Organic matter content**
  - C promotes P mineralization
- Aeration
  - Aeration promotes adsorption
- Eh
  - More available when oxidized
  - Reduced form is prone to leaching

Photo courtesy of UMN

Why use wastewater?

- Byproduct that is reported to supply >70% of P for plant growth (Davand et al.)
  - Through precipitation of struvite (Omidire, 2022)
- Sustainable alternative to rock phosphate
- Environmental concerns and application limits
  - Depends on the industry

Can we modify wastewater for use as a source of P fertilizer?

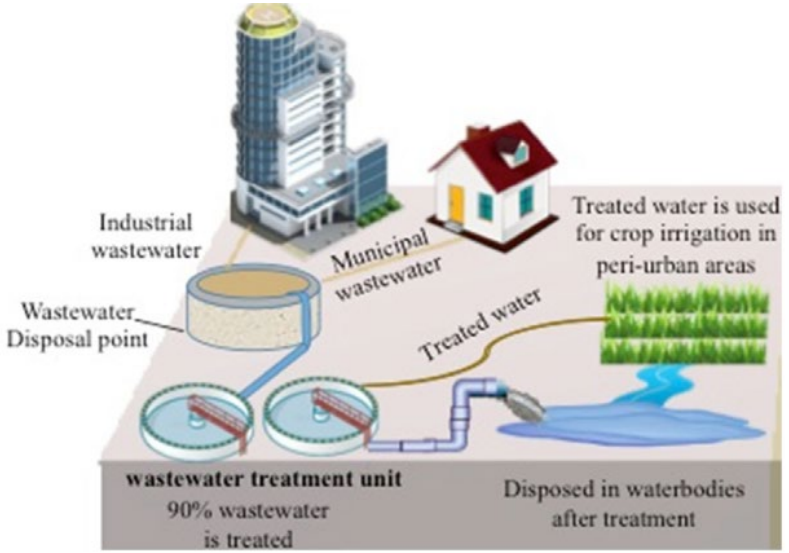


Photo courtesy of Davand, et al, 2022

Wastewater composition

- Water was collected in West Azerbaijan, Iran
  - 70% domestic & 30% Industrial
- We are not interested in EC or BOD
  - Do not impact the ions within water
  - Tells you about those ions at a specific condition
- TOC → acetate
- IC → carbon

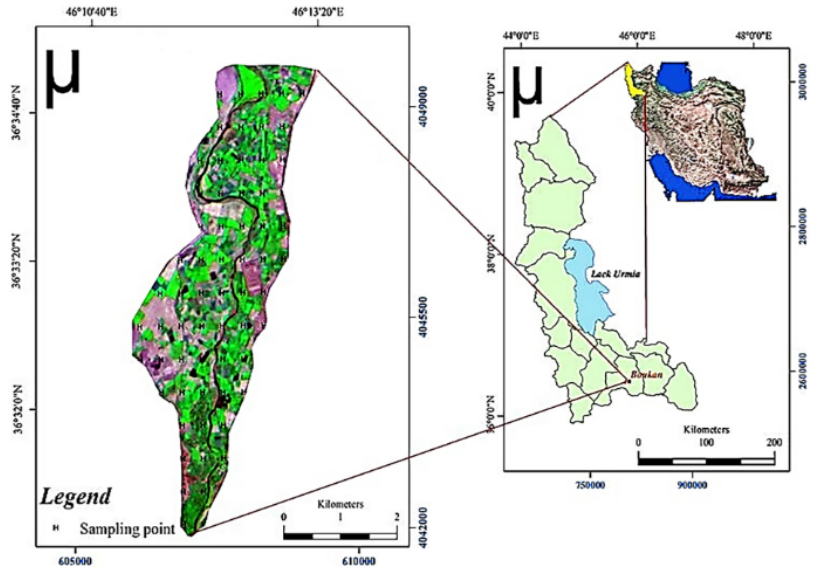


Fig. 1. Location map of the soil sampling area, Boukan province, West Azarbaijan, Iran.

	pH	EC ($dS\ m^{-1}$)	BOD_5 ($mg\ L^{-1}$)	COD	TOC	IC	PO_4	Cd ($\mu g\ L^{-1}$)	Cu	Co	Ni	Pb	Zn
Treated wastewater	7.82	6.04	20	40	33.8	135	7.5	1.20	8.52	0.027	12.12	45.31	325

Original output

----------Description of solution----------

pH	=	7.820
pe	=	4.000
Density (g/cm3)	=	0.99710
Volume (L)	=	1.00297
Viscosity (mPa s)	=	0.89002
Activity of water	=	1.000
Ionic strength (mol/kgw)	=	7.162e-04
Mass of water (kg)	=	1.000e+00
Total alkalinity (eq/kg)	=	7.740e-04
Total CO2 (mol/kg)	=	2.250e-06
Temperature (oC)	=	25.00
Electrical balance (eq)	=	-1.006e-03
Percent error, 100*(Cat-|An|)/(Cat+|An|)	=	-98.08
Iterations	=	10
Total H	=	1.110140e+02
Total O	=	5.550781e+01

Species	Molality	Activity	Log Molality	Log Activity	Log Gamma	mole V cm3/mol
P	2.422e-04					
HPO4-2	1.988e-04	1.762e-04	-3.702	-3.754	-0.052	(0)
H2PO4-	4.336e-05	4.208e-05	-4.363	-4.376	-0.013	(0)
PO4-3	6.453e-09	4.910e-09	-8.190	-8.309	-0.119	(0)
H3PO4	8.955e-11	8.955e-11	-10.048	-10.048	0.000	(0)
CoHPO4	6.503e-11	6.503e-11	-10.187	-10.187	0.000	(0)

PO_4^- & pH

- What if we change pH?
  - Optimal pH of wastewater is between 6.5 to 8.5 (J mark)

----------Description of solution----------

pH	= 6.500
pe	= 4.000
Density (g/cm3)	= 0.99710
Volume (L)	= 1.00297
Viscosity (mPa s)	= 0.89002
Activity of water	= 1.000
Ionic strength (mol/kgw)	= 4.776e-04
Mass of water (kg)	= 1.000e+00
Total alkalinity (eq/kg)	= 6.062e-04
Total CO2 (mol/kg)	= 2.250e-06
Temperature (oC)	= 25.00
Electrical balance (eq)	= -8.380e-04
Percent error, 100*(Cat-|An|)/(Cat+|An|)	= -97.54
Iterations	= 12
Total H	= 1.110141e+02
Total O	= 5.550781e+01

Species	Molality	Activity	Log Molality	Log Activity	Log Gamma	mole V cm3/mol
P	2.422e-04					
H2PO4-	1.991e-04	1.943e-04	-3.701	-3.712	-0.011	(0)
HPO4-2	4.300e-05	3.894e-05	-4.367	-4.410	-0.043	(0)
H3PO4	8.638e-09	8.638e-09	-8.064	-8.064	0.000	(0)
PO4-3	6.500e-11	5.193e-11	-10.187	-10.285	-0.098	(0)
CoHPO4	1.671e-11	1.671e-11	-10.777	-10.777	0.000	(0)

----------Description of solution----------

pH	= 8.500
pe	= 4.000
Density (g/cm3)	= 0.99710
Volume (L)	= 1.00297
Viscosity (mPa s)	= 0.89002
Activity of water	= 1.000
Ionic strength (mol/kgw)	= 7.651e-04
Mass of water (kg)	= 1.000e+00
Total alkalinity (eq/kg)	= 8.118e-04
Total CO2 (mol/kg)	= 2.250e-06
Temperature (oC)	= 25.00
Electrical balance (eq)	= -1.044e-03
Percent error, 100*(Cat-|An|)/(Cat+|An|)	= -98.46
Iterations	= 10
Total H	= 1.110139e+02
Total O	= 5.550781e+01

Species	Molality	Activity	Log Molality	Log Activity	Log Gamma	mole V cm3/mol
P	2.422e-04					
HPO4-2	2.316e-04	2.045e-04	-3.635	-3.689	-0.054	(0)
H2PO4-	1.052e-05	1.020e-05	-4.978	-4.991	-0.013	(0)
PO4-3	3.616e-08	2.727e-08	-7.442	-7.564	-0.122	(0)
CoHPO4	7.011e-11	7.011e-11	-10.154	-10.154	0.000	(0)
H3PO4	4.537e-12	4.537e-12	-11.343	-11.343	0.000	(0)

Changing Fe and Al activities

- More Fe and Al are available to bind with PO4
  - Less available solution P
- Legal limits: (*LIQTECH)*

  Al < 0.2 ppm

Species	Molality	Activity	Log Molality	Log Activity	Log Gamma	mole V cm3/mol
Al	7.413e-06					
Al(OH)4-	7.321e-06	7.103e-06	-5.135	-5.149	-0.013	(0)
Al(OH)3	8.481e-08	8.481e-08	-7.072	-7.072	0.000	(0)
Al(OH)2+	6.584e-09	6.389e-09	-8.181	-8.195	-0.013	(0)
AlOH+2	1.364e-11	1.209e-11	-10.865	-10.918	-0.052	(0)
Al+3	2.390e-14	1.817e-14	-13.622	-13.741	-0.119	(0)
P	2.422e-04					
HPO4-2	1.988e-04	1.762e-04	-3.702	-3.754	-0.052	(0)
H2PO4-	4.335e-05	4.207e-05	-4.363	-4.376	-0.013	(0)
PO4-3	6.455e-09	4.909e-09	-8.190	-8.309	-0.119	(0)
H3PO4	8.953e-11	8.953e-11	-10.048	-10.048	0.000	(0)
CoHPO4	6.499e-11	6.499e-11	-10.187	-10.187	0.000	(0)

Fe < 7 ppm

Species	Molality	Activity	Log Molality	Log Activity	Log Gamma	mole V cm3/mol
Fe(2)	1.274e-06					
Fe+2	7.630e-07	6.707e-07	-6.117	-6.173	-0.056	(0)
FeHPO4	4.684e-07	4.684e-07	-6.329	-6.329	0.000	(0)
FeOH+	1.832e-08	1.776e-08	-7.737	-7.750	-0.013	(0)
FeH2PO4+	1.452e-08	1.408e-08	-7.838	-7.851	-0.013	(0)
Fe(3)	1.241e-04					
Fe(OH)2+	7.143e-05	6.926e-05	-4.146	-4.160	-0.013	(0)
Fe(OH)3	4.949e-05	4.949e-05	-4.306	-4.306	0.000	(0)
Fe(OH)4-	3.161e-06	3.065e-06	-5.500	-5.514	-0.013	(0)
FeHPO4+	9.310e-10	9.028e-10	-9.031	-9.044	-0.013	(0)
FeOH+2	3.028e-10	2.676e-10	-9.519	-9.572	-0.054	(0)
Fe(Acetate)2+	7.386e-15	7.151e-15	-14.132	-14.146	-0.014	(0)
Fe(Acetate)+2	4.147e-15	3.645e-15	-14.382	-14.438	-0.056	(0)
Fe+3	8.245e-16	6.230e-16	-15.084	-15.205	-0.122	(0)
FeH2PO4+2	5.604e-16	4.955e-16	-15.251	-15.305	-0.053	(0)
P	2.422e-04					
HPO4-2	1.985e-04	1.754e-04	-3.702	-3.756	-0.054	(0)
H2PO4-	4.319e-05	4.189e-05	-4.365	-4.378	-0.013	(0)
FeHPO4	4.684e-07	4.684e-07	-6.329	-6.329	0.000	(0)
FeH2PO4+	1.452e-08	1.408e-08	-7.838	-7.851	-0.013	(0)
PO4-3	6.468e-09	4.887e-09	-8.189	-8.311	-0.122	(0)
FeHPO4+	9.310e-10	9.028e-10	-9.031	-9.044	-0.013	(0)
H3PO4	8.914e-11	8.914e-11	-10.050	-10.050	0.000	(0)
CoHPO4	6.459e-11	6.459e-11	-10.190	-10.190	0.000	(0)
FeH2PO4+2	5.604e-16	4.955e-16	-15.251	-15.305	-0.053	(0)

PO_4^- & organic carbon

- Increasing carbon results in P mineralization
  - Double the amount of SOC

```
----------------------------Description of solution----------------------------

                                    pH  =   7.820
                                    pe  =   4.000
                               Density (g/cm3)  =   0.99727
                                    Volume (L)  =   1.00297
                               Viscosity (mPa s)  =   0.89003
                               Activity of water  =   1.000
                          Ionic strength (mol/kgw)  =   2.068e-03
                               Mass of water (kg)  =   1.000e+00
                          Total alkalinity (eq/kg)  =   3.466e-03
                               Total CO2 (mol/kg)  =   2.250e-03
                                 Temperature (oC)  =  25.00
                           Electrical balance (eq)  =  -3.698e-03
        Percent error, 100*(Cat-|An|)/(Cat+|An|)  = -99.64
                                    Iterations  =  10
                                       Total H  = 1.110162e+02
                                       Total O  = 5.551448e+01

P                 2.422e-04
   HPO4-2              2.009e-04    1.647e-04     -3.697     -3.783     -0.086       (0)
   H2PO4-              4.131e-05    3.932e-05     -4.384     -4.405     -0.021       (0)
   PO4-3               7.218e-09    4.588e-09     -8.142     -8.338     -0.197       (0)
   H3PO4               8.368e-11    8.368e-11    -10.077    -10.077      0.000       (0)
   CoHPO4              4.761e-11    4.761e-11    -10.322    -10.322      0.000       (0)
```

Takeaways

For this particular wastewater:

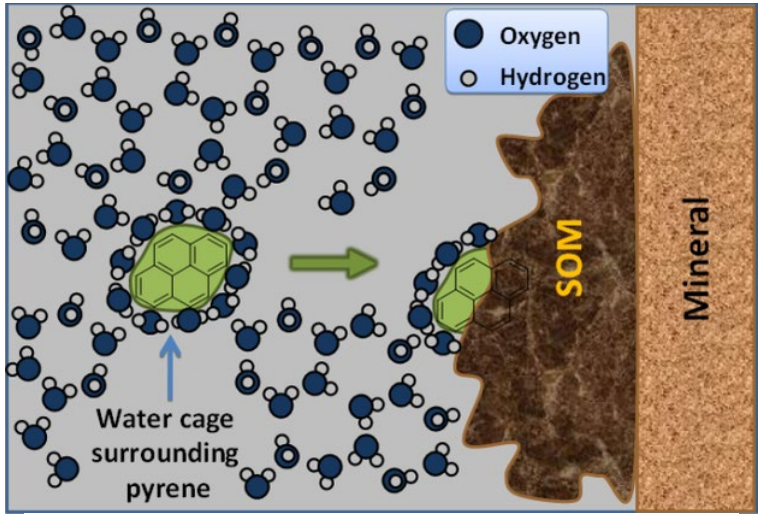
- PO_4^{3-} is higher at higher pH
- Fe and Al don't really impact available P
- Increasing SOC doesn't impact available P

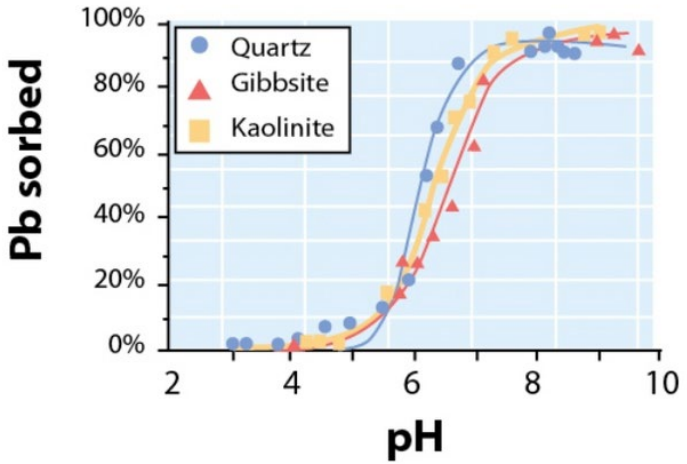
We can modify wastewater to serve as a viable source of P

- May not be economically feasible
- Within legal application limits

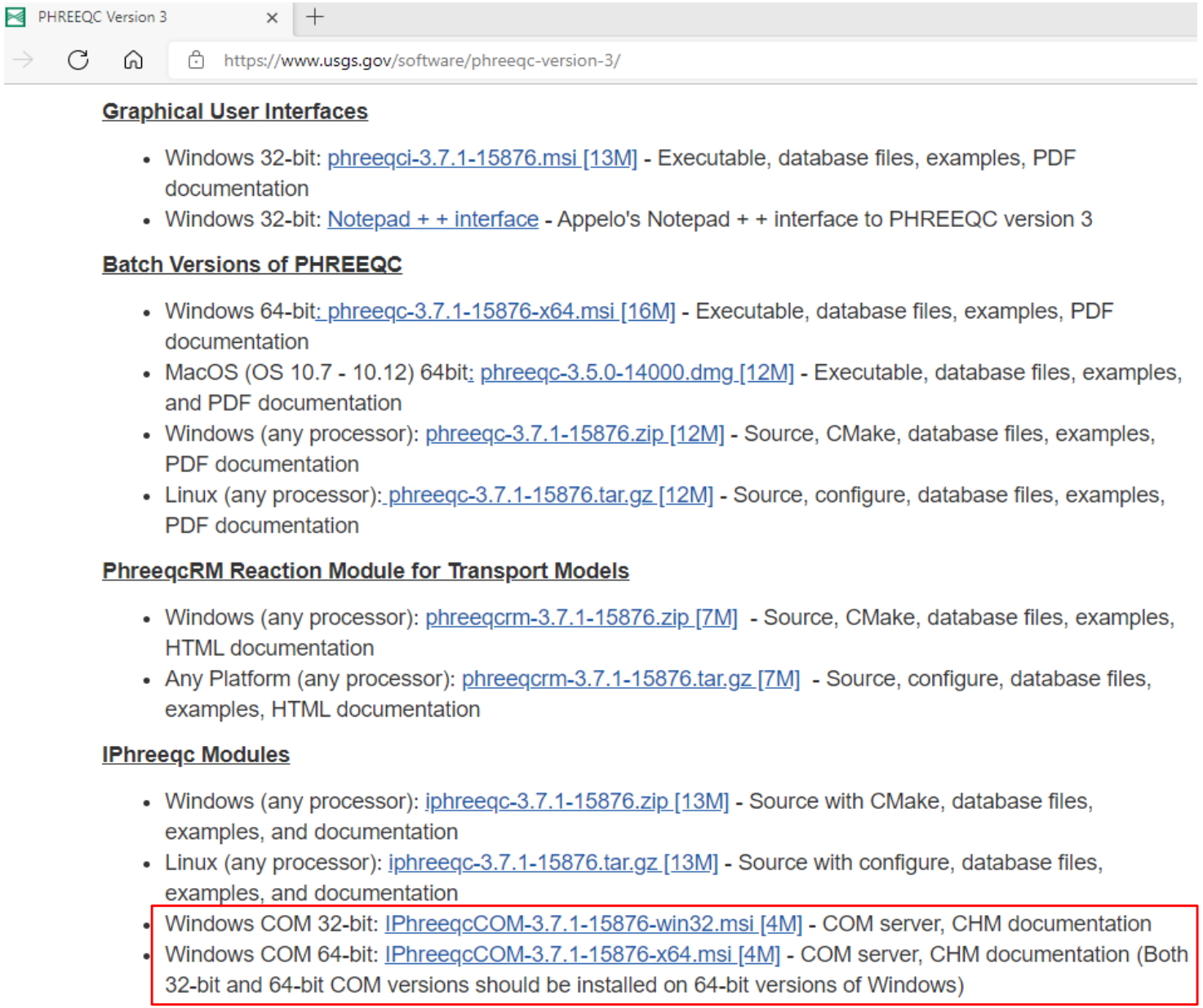
Modeling P sorption in PHREEQ

- Sorption is how sticky something is to a surface
- Phosphate is an anion
  - Cannot be modeled in PHREEQc
  - Davand, et. al, models in a different software
- Utilize PHREEQ-N-Titration-PO4-Adsorption Model
  - coding program developed in 2021 by USGS & Pennsylvania Water Science Center
  - Single or mixed solutions
  - Stagnant or flowing
  - Can be modeled on a mass or mol basis

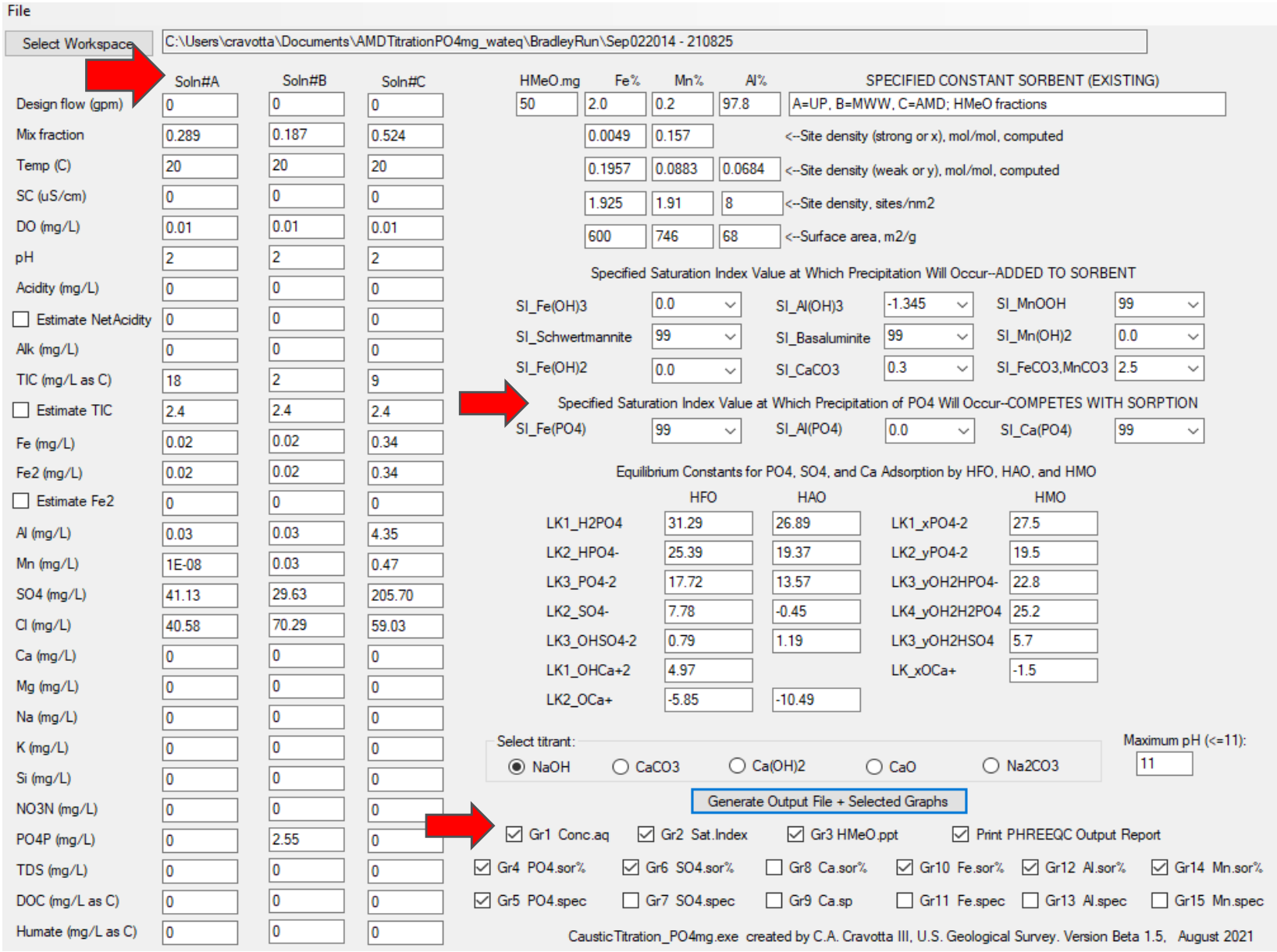




Photos courtesy of Nature Education



IPhreeqc runs in the background of the PO_4^{3-} sorption GUI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Soln#A
Soln#B
Soln#C
Design flow (gpm) 0 0 0
Mix fraction 0.289 0.187 0.524
Temp (C) 20 20 20
SC (uS/cm) 0 0 0
DO (mg/L) 0.01 0.01 0.01
pH 2 2 2
Acidity (mg/L) 0 0 0
Estimate NetAcidity 0 0 0
Alk (mg/L) 0 0 0
TIC (mg/L as C) 18 2 9
Estimate TIC 2.4 2.4 2.4
Fe (mg/L) 0.02 0.02 0.34
Fe2 (mg/L) 0.02 0.02 0.34
Estimate Fe2 0 0 0
Al (mg/L) 0.03 0.03 4.35
Mn (mg/L) 1E-08 0.03 0.47
SO4 (mg/L) 41.13 29.63 205.70
Cl (mg/L) 40.58 70.29 59.03
Ca (mg/L) 0 0 0
Mg (mg/L) 0 0 0
Na (mg/L) 0 0 0
K (mg/L) 0 0 0
Si (mg/L) 0 0 0
NO3N (mg/L) 0 0 0
PO4P (mg/L) 0 2.55 0
TDS (mg/L) 0 0 0
DOC (mg/L as C) 0 0 0
Humate (mg/L as C) 0 0 0
HMeO.mg Fe% Mn% Al% SPECIFIED CONSTANT SORBENT (EXISTING)
50 2.0 0.2 97.8 A=UP, B=MWW, C=AMD; HMeO fractions
0.0049 0.157 <--Site density (strong or x), mol/mol, computed
0.1957 0.0883 0.0684 <--Site density (weak or y), mol/mol, computed
1.925 1.91 8 <--Site density, sites/nm2
600 746 68 <--Surface area, m2/g
Specified Saturation Index Value at Which Precipitation Will Occur--ADDED TO SORBENT
SI_Fe(OH)3 0.0 SI_Al(OH)3 -1.345 SI_MnOOH 99
SI_Schwertmannite 99 SI_Basaluminite 99 SI_Mn(OH)2 0.0
SI_Fe(OH)2 0.0 SI_CaCO3 0.3 SI_FeCO3,MnCO3 2.5
Specified Saturation Index Value at Which Precipitation of PO4 Will Occur--COMPETES WITH SORPTION
SI_Fe(PO4) 99 SI_Al(PO4) 0.0 SI_Ca(PO4) 99
Equilibrium Constants for PO4, SO4, and Ca Adsorption by HFO, HAO, and HMO
HFO HAO HMO
LK1_H2PO4 31.29 26.89 LK1_xPO4-2 27.5
LK2_HPO4- 25.39 19.37 LK2_yPO4-2 19.5
LK3_PO4-2 17.72 13.57 LK3_yOH2HPO4- 22.8
LK2_SO4- 7.78 -0.45 LK4_yOH2H2PO4 25.2
LK3_OHSO4-2 0.79 1.19 LK3_yOH2HSO4 5.7
LK1_OHCa+2 4.97 LK_xOCa+ -1.5
LK2_OCa+ -5.85 -10.49
Select titrant:
NaOH CaCO3 Ca(OH)2 CaO Na2CO3
Maximum pH (<=11):
11
Generate Output File + Selected Graphs
Gr1 Conc.aq Gr2 Sat.Index Gr3 HMeO.ppt Print PHREEQC Output Report
Gr4 PO4.sor% Gr6 SO4.sor% Gr8 Ca.sor% Gr10 Fe.sor% Gr12 Al.sor% Gr14 Mn.sor%
Gr5 PO4.spec Gr7 SO4.spec Gr9 Ca.sp Gr11 Fe.spec Gr13 Al.spec Gr15 Mn.spec
CausticTitration_PO4mg.exe created by C.A. Cravotta III, U.S. Geological Survey. Version Beta 1.5, August 2021

The Bradley Run Case

- Spellman et al., 2021
  - This example is programmed into the downloaded zip file
- Simulates the interaction of stream water, municipal wastewater and mine drainage
- Shows that P sorption is impacted by available quantity of previously accumulated HMeO sorbent
- PO_4^{3-} is able to precipitate and thus sorb by reducing (Al)
  - Adjusts the of gibbsite and $Al(OH)_3$

Form1

File

Select Workspace | C:\PHREEQc\phreeq-n-titration-po4-adsorption-v1.0.0

	Soln#A	Soln#B	Soln#C
Design flow (gpm)	0	0	0
Mix fraction	0.289	0.187	0.524
Temp (C)	20	20	20
SC (uS/cm)	0	0	0
DO (mg/L)	0.01	0.01	0.01
pH	2	2	2
Acidity (mg/L)	0	0	0
☐ Estimate NetAcidity	*0*	*0*	*0*
Alk (mg/L)	0	0	0
TIC (mg/L as C)	18	2	9
☐ Estimate TIC	*2.4*	*2.4*	*2.4*
Fe (mg/L)	0.02	0.02	0.34
Fe2 (mg/L)	0.02	0.02	0.34
☐ Estimate Fe2	*0*	*0*	*0*
Al (mg/L)	0.03	0.03	4.35
Mn (mg/L)	1E-08	0.03	0.47
SO4 (mg/L)	41.13	29.63	205.70
Cl (mg/L)	40.58	70.29	59.03
Ca (mg/L)	0	0	0
Mg (mg/L)	0	0	0
Na (mg/L)	0	0	0
K (mg/L)	0	0	0
Si (mg/L)	0	0	0
NO3N (mg/L)	0	0	0
PO4P (mg/L)	0	2.55	0
TDS (mg/L)	0	0	0

HMeO.mg	Fe%	Mn%	Al%	SPECIFIED CONSTANT SORBENT (EXISTING)			
0	2.0	0.2	97.8	A=UP, B=MWW, C=AMD; HMeO fractions			
	0.0049	*0.157*		*<--Site density (strong or x), mol/mol, computed*			
	0.1957	*0.0883*	*0.0684*	*<--Site density (weak or y), mol/mol, computed*			
	1.925	1.91	8	<--Site density, sites/nm2			
	600	746	68	<--Surface area, m2/g	*62736.6*	*77324.4*	*5147.3* *Surface area, m2/mol, comp.*

Specified Saturation Index Value at Which Precipitation Will Occur--ADDED TO SORBENT

SI_Fe(OH)3	0.0	SI_Al(OH)3	-1.345	SI_MnOOH	99
SI_Schwertmannite	99	SI_Basaluminite	99	SI_Mn(OH)2	0.0
SI_Fe(OH)2	0.0	SI_CaCO3	0.3	SI_FeCO3,MnCO3	2.5

Specified Saturation Index Value at Which Precipitation of PO4 Will Occur--COMPETES WITH SORPTION

SI_Fe(PO4)	99	SI_Al(PO4)	0.0	SI_Ca(PO4)	99

Equilibrium Constants for PO4, SO4, and Ca Adsorption by HFO, HAO, and HMO

	HFO	HAO		HMO
LK1_H2PO4	31.29	26.89	LK1_xPO4-2	27.5
LK2_HPO4-	25.39	19.37	LK2_yPO4-2	19.5
LK3_PO4-2	17.72	13.57	LK3_yOH2HPO4-	22.8
LK2_SO4-	7.78	-0.45	LK4_yOH2H2PO4	25.2
LK3_OHSO4-2	0.79	1.19	LK3_yOH2HSO4	5.7
LK1_OHCa+2	4.97		LK_xOCa+	-1.5
LK2_OCa+	-5.85	-10.49		

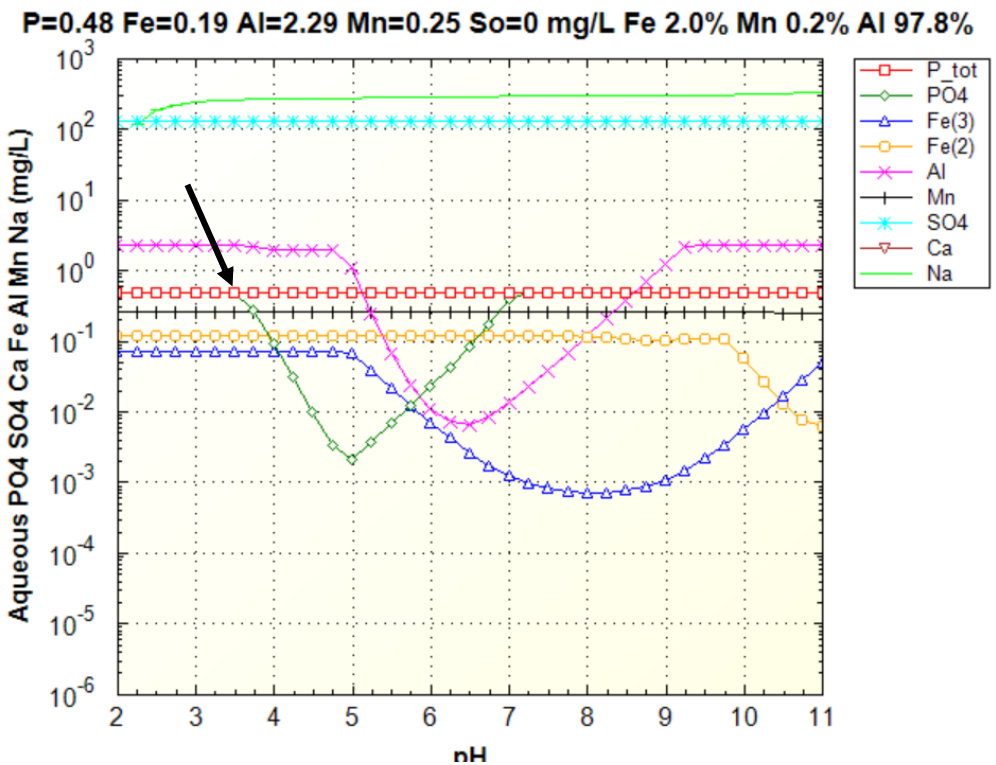
Select titrant: ◉ NaOH ○ CaCO3 ○ Ca(OH)2 ○ CaO ○ Na2CO3

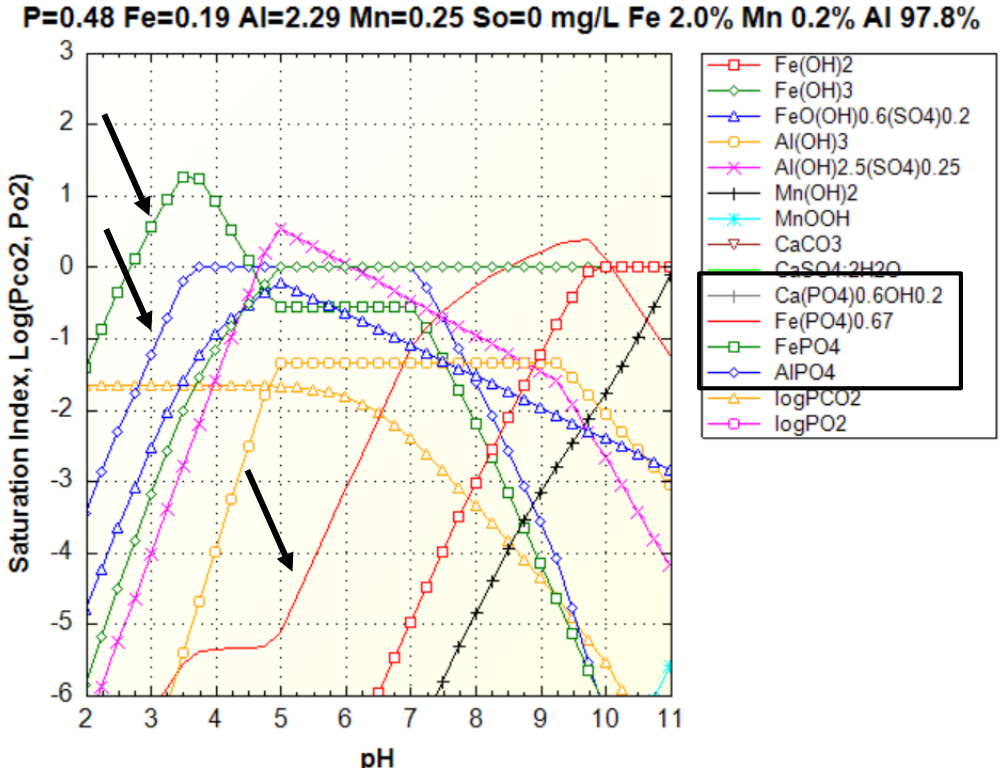
Maximum pH (<=11): 11

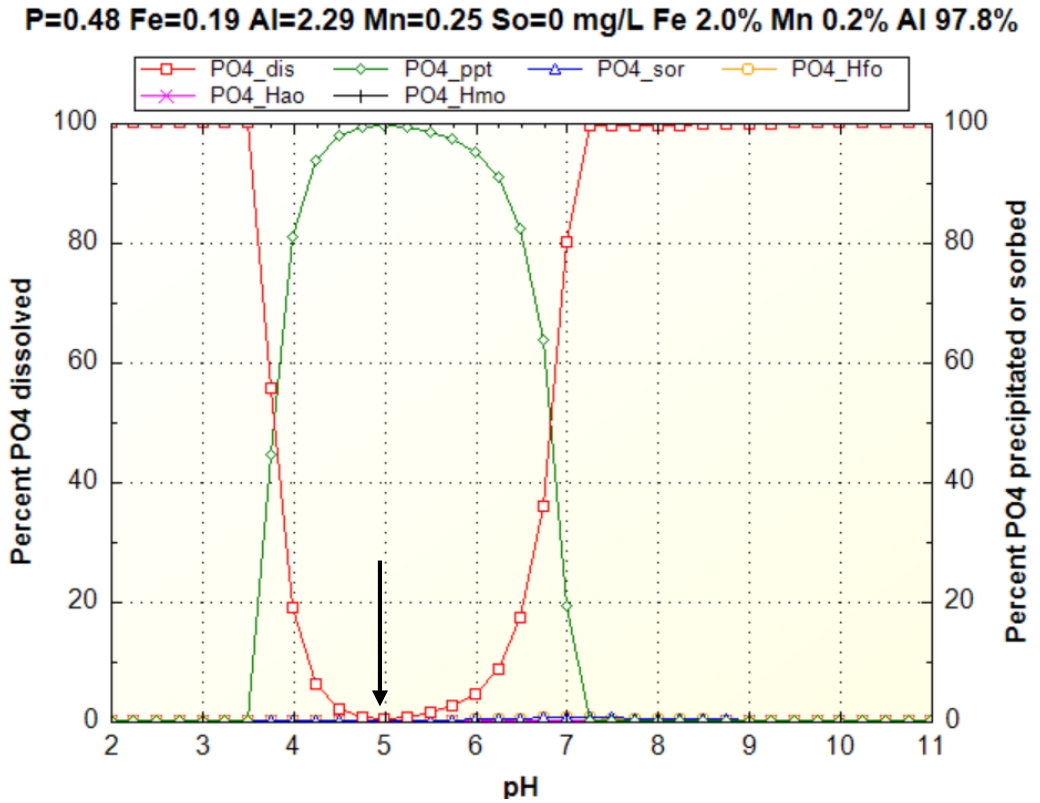
Generate Output File + Selected Graphs

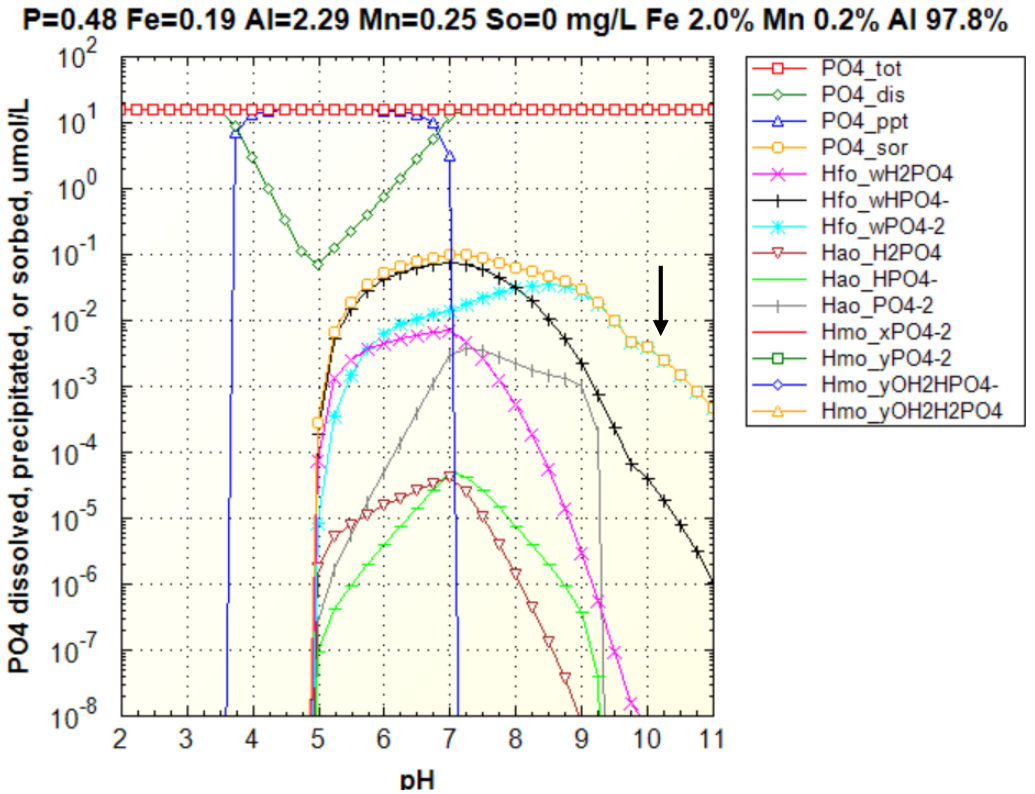
☑ Gr1 Conc.aq ☑ Gr2 Sat.Index ☐ Gr3 HMeO.ppt ☐ Print PHREEQC Output Report

☑ Gr4 PO4.sor% ☐ Gr6 SO4.sor% ☐ Gr8 Ca.sor% ☐ Gr10 Fe.sor% ☐ Gr12 Al.sor% ☐ Gr14 Mn.sor%


P=0.48 Fe=0.19 Al=2.29 Mn=0.25 So=0 mg/L Fe 2.0% Mn 0.2% Al 97.8%
Aqueous PO4 SO4 Ca Fe Al Mn Na (mg/L)
pH
P_tot
PO4
Fe(3)
Fe(2)
Al
Mn
SO4
Ca
Na


P=0.48 Fe=0.19 Al=2.29 Mn=0.25 So=0 mg/L Fe 2.0% Mn 0.2% Al 97.8%
Saturation Index, Log(Pco2, Po2)
pH
Fe(OH)2
Fe(OH)3
FeO(OH)0.6(SO4)0.2
Al(OH)3
Al(OH)2.5(SO4)0.25
Mn(OH)2
MnOOH
CaCO3
CaSO4:2H2O
Ca(PO4)0.6OH0.2
Fe(PO4)0.67
FePO4
AlPO4
logPCO2
logPO2


P=0.48 Fe=0.19 Al=2.29 Mn=0.25 So=0 mg/L Fe 2.0% Mn 0.2% Al 97.8%
PO4_dis
PO4_ppt
PO4_sor
PO4_Hfo
PO4_Hao
PO4_Hmo
Percent PO4 dissolved
Percent PO4 precipitated or sorbed
pH


P=0.48 Fe=0.19 Al=2.29 Mn=0.25 So=0 mg/L Fe 2.0% Mn 0.2% Al 97.8%
PO4_tot
PO4_dis
PO4_ppt
PO4_sor
Hfo_wH2PO4
Hfo_wHPO4-
Hfo_wPO4-2
Hao_H2PO4
Hao_HPO4-
Hao_PO4-2
Hmo_xPO4-2
Hmo_yPO4-2
Hmo_yOH2HPO4-
Hmo_yOH2H2PO4
PO4 dissolved, precipitated, or sorbed, umol/L
pH

Conclusions

- We can now model sorption of both anions and cations!
  - Informs management practices to avoid P loss
  - Can be used for a wide variety of scenarios
- Lots more to be done and learn
  - In order to model this particular water, we would need to add ions to the database
- For more information this software download can be found on the summary sheet

References

- Benavente, D., Brimblecombe, P., & Grossi, C. M. (2015). Thermodynamic calculations for the salt crystallisation damage in porous built heritage using PHREEQC. *Environmental Earth Sciences*, *74*(3), 2297–2313. https://doi.org/10.1007/s12665-015-4221-1

- Carrillo, V., Fuentes, B., Gómez, G., & Vidal, G. (2020). Characterization and recovery of phosphorus from wastewater by combined technologies. *Reviews in Environmental Science and Bio/Technology*, *19*(2), 389–418. https://doi.org/10.1007/s11157-020-09533-1

- Davand, H., Sepehr, E., Momtaz, H. R., & Ahmadi, F. (2022). Wastewater irrigation: An opportunity for improving soil phosphorus availability; PHREEQC modeling and adsorption studies. *Science of The Total Environment*, *851*, 158180. https://doi.org/10.1016/j.scitotenv.2022.158180

- *Greisheim, K. (2025) Soil Fertility and Fertilizers: Lecture 4B (Essential Nutrients: Phosphorous). North Dakota State University.*

- *Interactive PHREEQ-N-Titration-PO4-Adsorption water-quality modeling tools to evaluate potential attenuation of phosphate and associated dissolved constituents by aqueous-solid equilibrium processes (software download) | U.S. Geological Survey*. (2022, January 11). https://www.usgs.gov/software/interactive-phreeq-n-titration-po4-adsorption-water-quality-modeling-tools-evaluate

- "Industrial Wastewater Discharge Limits and Requirements." *LIQTECH.* Accessed April 28, 2025. https://liqtech.com/systems/industrial-wastewater/industrial-wastewater-discharge-limits-and-requirements/.

- Li, Zhiwei, Hongwu Tang, Yang Xiao, Hanqing Zhao, Qingxia Li, and Fei Ji. "Factors Influencing Phosphorus Adsorption onto Sediment in a Dynamic Environment." *Journal of Hydro-Environment Research* 10 (March 1, 2016): 1–11. https://doi.org/10.1016/j.jher.2015.06.002.

- Nguyen, Minh Duc, Sirjana Adhikari, Deepak Surendhra Mallya, Michael Thomas, Aravind Surapaneni, Ellen M. Moon, and Nicholas A Milne. "Reuse of Aluminium-Based Water Treatment Sludge for Phosphorus Adsorption: Evaluating the Factors Affecting and Correlation between Adsorption and Sludge Properties." *Environmental Technology & Innovation* 27 (August 1, 2022): 102717. https://doi.org/10.1016/j.eti.2022.102717.

- Parkhurst, D. L., & Appelo, C. a. J. (2013). Description of input and examples for PHREEQC version 3: A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. In *Techniques and Methods* (Nos. 6-A43). U.S. Geological Survey. https://doi.org/10.3133/tm6A43

- Spellman, Charles D., Peter M. Smyntek, Charles A. Cravotta, Travis L. Tasker, and William H. J. Strosnider. "Pollutant Co-Attenuation via in-Stream Interactions between Mine Drainage and Municipal Wastewater." *Water Research* 214 (May 1, 2022): 118173. https://doi.org/10.1016/j.watres.2022.118173.

- Torit, Jirawan, and Doungkamon Phihusut. "Phosphorus Removal from Wastewater Using Eggshell Ash." *Environmental Science and Pollution Research* 26, no. 33 (November 1, 2019): 34101–9. https://doi.org/10.1007/s11356-018-3305-3.

Pictures

- https://www.iisd.org/ela/blog/back-to-basics-how-and-why-phosphorus-cycles-through-a-lake/
- https://www.mindat.org/photo-409848.html
- https://blog-crop-news.extension.umn.edu/2020/03/how-to-prevent-fallow-syndrome-in-corn.html
- https://www.nature.com/scitable/knowledge/library/introduction-to-the-sorption-of-chemical-constituents-94841002/