USERS MANUAL: PHOSPHORUS AND WATER BALANCE TOOLS FOR TMDL PLANS

L.A., Baker[1], H.L. Peterson[1,2], D. Bruening[2]J. Nieber[1], B.N, Wilson[1], J. Ulrich[1,3]

[1]University of Minnesota

[2] Now at Minnesota Department of Agriculture

[3] Now at EOR Consulting

This Users Manual is an outcome of a project "Phosphorus and Water Balance Tools for TMDL Plans", an EPA/MCPA "319" project. Our broad goal was to develop new tools for managing nonpoint sources of phosphorus in both agricultural and urban watersheds.

Several other products from this project would benefit potential users:

- Peterson, H.M., L. A. Baker, J.S. Ulrich, D. Bruening, J.L. Nieber, and B. N. Wilson. *Agricultural system phosphorus balance for addressing watershed TMDL goals*. To be submitted to *J. Environmental Quality*.
- Baker, L.A., H.M. Peterson, J.S. Ulrich, D. Bruening, J.L. Nieber, and B. N. Wilson. *Phosphorus Balances for the Albert Lea Region.* Report to the Shell Rock River Watershed District, September 2014.
- Two Excel spreadsheets, the Agricultural P Balance Calculator and the Urban P Balance Calculator.

The first paper develops what is perhaps the most detailed P balance ever constructed for a large agricultural watershed. To do this, we used on-site farm surveys to gain information regarding crop management practices, "drive-by" surveys of animal operations to verify numbers from feedlot permit data, used high resolution crop mapping from NASS, analyzed three years of monitoring data to compute stream P loads, and embedded local expert knowledge gained from farmers and academic livestock experts. The Peterson et al. paper describes the methodology and the overall P balance in detail.

The knowledge acquired was embedded in our **Agricultural P Balance Calculator**, an open-source, Excel-based spreadsheet tool. The model is designed to allow the user to simulate a variety of scenarios, especially for animal operations. For example, the P balance algorithms for each animal operation allow the user to modify the herd structure, change nutrient inputs in relation to changes in production, alter the feedstocks used to produce animal feeds, and estimate changes in manure P fluxes in response to management practices.

The parallel **Urban P Balance Calculator** enables the user to develop P balances for cities. The knowledge embedded in this calculator was gained over many years of study of P in urban systems, including a major study of household biogeochemical flows (Baker et al. 2007, Fissore et al. 2011, 2012), a study of nutrient dynamics of urban stormwater (Janke et al. 2014), and a P balance for the Twin Cities (Baker 2011).

Finally, we examined the hydrology and biogeochemistry of surface waters in the three agricultural subwatersheds to develop **Biogeochemical Diagnostics Tools** to enable users to better understand flowpaths of P, and thereby develop more effective BMPs.

Taken together, these tools have the potential to inform total maximum daily load (TMDL) plans. To date, the primary focus of nonpoint source TMDL reductions has been based on structural BMPs installed at the end-of-the-pipe or edge-of-the-field. This has proven to be expensive, and not very effective at the scale of large watersheds. Moving our thinking upstream – toward understanding P balances – could lead to a fundamental re-thinking of how we manage nonpoint source P pollution.

"P balance thinking" can move users closer to understanding the penultimate sources of P entering the watershed, how P is transferred within watersheds, and the efficiency of P utilization. For example, Peterson et al. (2014) concluded that importing piglets, rather than breeding sows within the watershed, increased the P use efficiency of hog operations by 12%. Similarly, our analysis of the P balance of the City of Albert Lea reveals that, with a state-wide lawn P fertilizer law in place, dog wastes are now the major P source to the urban landscape, and that increasing the pickup of dog wastes (transferring the P to garbage) could significantly alter the urban landscape P balance (see Section I). In a separate study (Kalinosky et al. 2014), we learned that removing tree leaves from streets before they enter storm drains can prevent large quantities of N and P, sometimes at a fraction of the cost of structural BMPs.

Our **Biogeochemical Diagnostics Tools** can also lead to improved selection of BMPs. This toolkit focuses on more in-depth analysis of data that is often collecting in monitoring studies, but ignored; an expanded suite of analytical measurements that can reveal information about hydrologic sources of P to a stream; and the use of synoptic surveys to understand spatial variability of P sources.

USER MANUAL PART I: URBAN P BALANCE CALCULATOR

This section provides the technical background for the **Urban P Balance Calculator**, the accompanying spreadsheet tool, and general guidance for using the Calculator. Users might also peruse our report, **Phosphorus Balances for the Albert Lea Region**, which includes urban P balances for households, industries, and urban landscapes using the Urban P Balance Calculator

Users can use the Urban P Balance Calculator to understand sources of P entering an urban system, how it is processed within the system, and how it leaves, both through *deliberate exports* (e.g., processed food) and *inadvertent exports*, such as stormwater runoff and treated sewage. "Urban Systems" are broken down into two separate components: the fully *engineered system*, in which P enters the watershed via food and various chemicals (industrial and household cleansers, etc.), transmitted via sewers to wastewater treatment plants, and disposed as effluent, which enters streams, rivers, and lakes; biosolids, which may be utilized in agriculture or disposed to landfills; and solid waste, generally disposed to landfills. The other system is *urban landscapes*, in which P enters the landscape outside homes and commercial and industrial buildings, and exits via stormwater drains or streams.

Data for our spreadsheet calculator is based on many studies, including several major studies conducted in the Twin Cities. Three of these are especially important for developing the Urban P Balance Calculator. The Twin Cities Household Ecosystem Study (TCHEP) developed household-level budgets for nitrogen, phosphorus, and carbon for 1,800 owner-occupied homes in the urbanized parts of Ramsey and Anoka Counties. Key findings are presented in several papers (Fissore et al. 2011, Fissore et al. 2012). A second study involved detailed analysis of chemical fluxes from major storm drains in the Capital Region Watershed District (CRWSD) based measurements by CRWSD over a three-year period, provided to our University of Minnesota group of urban ecosystem researchers and summarized by (Janke et al. 2013b). A third project was construction of a P balance for the Twin Cities region that included P fluxes from both the "fully engineered" and "urban landscape" systems (Baker 2011).

The use of coefficients derived outside the system being studied is necessary -- one could not construct a P balance from scratch using only measurements made within a city – but some P fluxes are more site-specific and more accurately determined from measurements. For example, it is relatively simple to develop a P balance for sewage treatment, and the resulting P fluxes will be much more accurate than estimates based on generic coefficients. For industries that have large P fluxes (such as food processing industries), the user will need to develop P balances based on in-plant surveys and other sources of data.

The Urban Spreadsheet Calculator handles many, but not all situations. The beauty of an open-source spreadsheet is that the user could easily add new algorithms to represent a novel situation.

SUBMODEL FOR THE ENGINEERED SUBSYSTEM

P Fluxes Through Households

P enters households, industries, and commercial establishments. Because humans consume food and excrete P both within their homes and in commercial establishments, we conceptualize all P fluxes through humans as though they are part of the "household", even if some activities that take place outside their physical living spaces (homes or apartments). For example, our coefficient for household food consumption incudes all eating, regardless of where the eating occurs.

The largest P input to many cities is human food. In TCHEP, we based on our estimate of caloric input per person based on a large survey (3,000 respondents), which inquired about age, height, gender, weight, and activity level for each household member. These data were then input to an energy equation to estimate caloric intake per person. We also asked a general question about the type of diet eaten (conventional, vegetarian, vegan), which was used to allocate calories into fats, proteins, carbohydrates, and fiber; and, in turn, total dry mass of food. We used the mean P content (0.3% of dry weight) to estimate P consumption per person, and then used U.S. Census data to "map" our TCHEP sample into the Twin Cities population based on age, race, ethnicity, and gender. This yielded a P flux of 0.6 kg P/capita-yr (cell B10 in the Urban P Balance Calculator). Details are presented in Fissore et al. (2011), which includes extensive web-accessible supplemental documentation, including all specific equations and data sources. An additional P flux into households is food that is wasted, about 0.24 kg/capita-year (cell B11). This food waste P either becomes garbage (solid waste) or enters a household garbage disposal (Kantor et al. 1997). Total food P entering a household system is therefore food consumed + food wasted, or 0.84 kg P/capita-yr.

Additional P enters households in various household chemicals. We estimated this flux by subtracting human excretion (= food consumed) from total wastewater P loading (obtained from Met Council), after accounting for food P entering sewage from garbage disposals, yielding an estimate of 0.61 kg/capita-year (cell B12).

Finally, P enters households via dog food. The coefficient used in the model is based on our TCHEP study, which queried households regarding the number of dogs, their sizes, the composition of dog food, and a metabolic equation for dog nutritional requirements (Baker et al. 2007, Fissore et al 2011). The actual coefficient is based on dog food P/household, 0.3 kg P/household-yr, then calculated on a per capita basis based on the number of members per household (this is on the Urban Landscape sheet).

Most P exits the household system by sewage or solid waste. Sewage P includes P in human excretion (= food P ingested), P in household chemicals, P entering sewers via garbage disposals, and P from dog wastes collected by owners that is disposed to garbage. We estimate that the P flux to garbage disposals is 0.05 kg/capita-yr in households with garbage disposals (cell B21), and 0 for households without garbage disposals. For households with garbage disposals, 0.05 kg P/capita-yr is subtracted from P in wasted food, resulting in 0.24-0.05 = 0.19 kg P/capita-yr being sent to solid waste.

P in dog excretion was partitioned into wastes picked up by owners and deposited into garbage, and waste not picked up, and left on landscapes. All P in urine (25% of total excretion) remained on landscapes; we used an estimate of 60% pickup, based on RDEQ (2003). The P in solid waste picked up was added to solid waste; the P left on the ground was added to the landscape flux, along with the P in urine.

Our estimate of total household P input to wastewater was 1.21 kg P/capita-year, not including industrial sources. This is very close to the mean value of 1.3 kg P/capita-year in sewage in a study of 17 homes with septic systems in which sewage P fluxes were measured directly (Lowe et al. 2009).

Table 1. Summary of coefficients used in the household component of the Urban Spreadsheet Model. Most values are from TCHEP Fissore et al. (2011).

Flux term	Coefficient, kg P/capita-yr
Human food	0.6
Food brought into households that is wasted	0.24
Dog food	0.13
Household chemicals	0.61
Flux to garbage disposals (if present)	0.05
Flux to sewage, with garbage disposal present	2.24
Flux to sewage, without garbage disposal	2.30
Flux to solid waste, with garbage disposal	0.19
Flux to solid waste, without garbage disposal	0.24

P exiting household as solid waste (garbage) might move to a landfill directly, which may or may not be in the watershed. In the Twin Cities (but less so in other Minnesota cities), some solid waste (including food) is incinerated. The ash from incineration, which contains all of the P in the original waste, is then disposed in landfills. The Urban Spreadsheet Calculator treats the P flux for incinerated and non-incinerated solid waste the same, since the P flux (kg P/yr) is the same either way.

To use the Urban P Balance Calculator, the user must specify the routing of solid waste P. The model requires input regarding the location of landfills (inside or outside the study area, cell B78).

Septic Systems
About 20% of homes in Minnesota use septic systems for sewage treatment. Briefly, septic systems move water through a septic tank, where some degradation of sewage occurs, along with sedimentation; and then to a leach field, which distributes the water via buried pipes with holes across a rectangul ar area, generally about three feet below the surface. P in household wastewater is either removed by sedimentation, becoming part of the septic system sludge; the soluble P then moves to a leach field, where it is either adsorbed in the subsurface soil, or, eventually, bleeds through the soil, entering groundwater, streams, or lakes.

Our coefficient for P removal in septic systems is based on the Lowe et al. (2004) study of 17 households across the U.S. They calculated a mean total P (TP) concentration of 10 mg P/L and a P loading of 1.3 kg P/capita-year. They also calculated a P removal rate of 30% (the default value in cell B38), which means that 0.4 kg P/capita-year becomes sludge and 0.9 kg P/capita-year is leached through the soil. The sludge from septic systems has to be removed periodically (often every several years). The pumped sludge is then transported by truck. Most commonly, septic system sludge is applied to cropland, or it is disposed to a sewage treatment plant, either directly or at some more distant point, through a disposal site to a main sewer line. The Urban Spreadsheet Calculator asks the user to indicate the fate of septic sludge. Cell B54 asks whether septic system biosolids are added to sewage ("yes" or "no"), and then Cell B76 asks what percentage of septic sludge is exported from the watershed (this should be "0" if B54 is "yes").

Sewage Treatment
For households connected to sewers, P nearly always enters wastewater treatment plants. Within wastewater treatment plants, some P is removed by sedimentation, either directly (particles in the sewage) or indirectly (by forming P-rich particles during the treatment process). P removal is often enhanced by biological processes, in which P is concentrated in microbes, which then settle in sedimentation basins, or by chemical flocculation, using iron or aluminum salts. Many larger wastewater treatment plants collect data on P concentrations and flows at both the inlet to the plant and the outlet. This allows a direct calculation of P removal efficiency:

$$P_{eff} = \sum_{n=1}^{12}[P_{in}\,Q_{in} - P_{out}\,Q_{out}] \qquad \text{equation 1}$$

Where P_{eff} is the P removal efficiency, $(P)_{in,\ out}$ = P concentrations in the influent and effluent, respectively, and $Q_{in,\ out}$ = flows of the influent and effluent.

The data needed to compute P removal in sewage treatment plants are often available from the operators of a particular plant, generally a sewage authority (such as Met Council in the Twin Cities) or a city engineering or public works department. For the our case study city of Albert Lea, the Public Works Department provide data on the influent and effluent P concentrations and flow by month, allowing us to calculate P removal by month. From this we were able to compute P removal for the year. The graphs below illustrate changes in P concentrations and flow throughout the year, which result in changes in monthly P removal (Figure 1 a-c). For this reason, monthly data throughout a year would be needed to derive an accurate P balance.

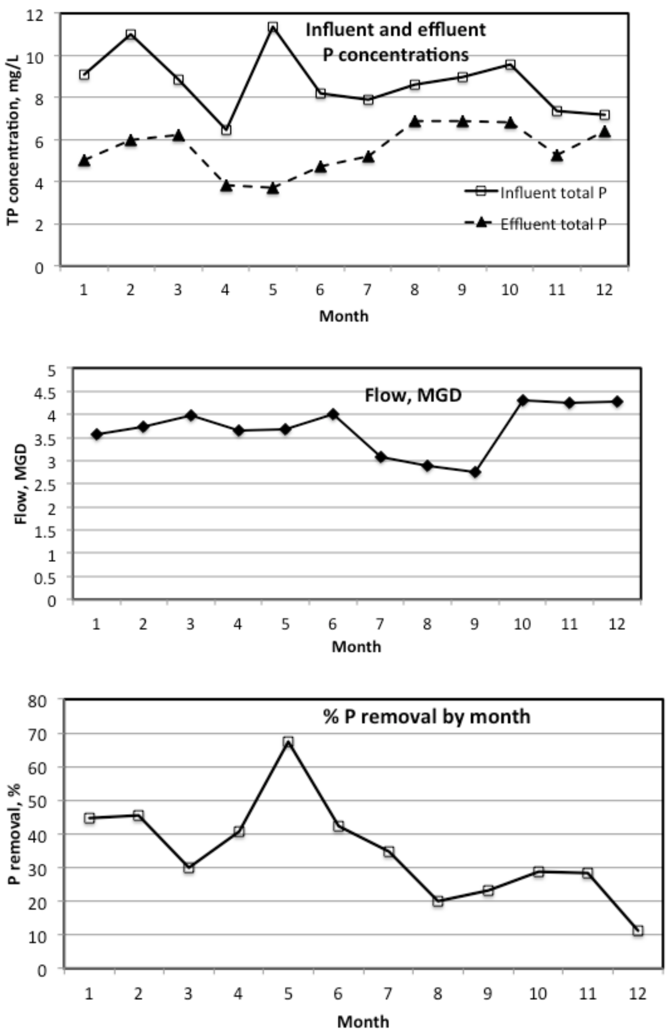

Figure 1. P removal in the Albert Lea Sewage Treatment Plant by month: (a) influent and effluent P concentrations, (b) P removal, and (c) % P removal.

Wastewater treatment plants in smaller cities and towns might not measure P concentrations in both influent and effluent, and possibly not in either. These types of cities might also use less advanced treatment systems, such as sewage ponds. For these situations, the user indicates with an "X" the type of sewage system in the town (cells B59-B62) and the Calculator uses default values for P removal (see Comments). For sewage ponds, a reasonable assumption for P removal is 50% (Metalf and Eddy, 1991; Reed 1995). P removals for secondary treatment and for advanced treatment are based on calculated values for Met Council treatment plants.

P that is "removed" from the influent of wastewater treatment plants becomes biosolids. Hence, the urban spreadsheet calculator apportions influent P as follows:

$$F_{biosolid} = \left\lfloor \sum_{n=1}^{12} Q_{in}\, P_{in} - \sum_{n=1}^{12} Q_{out}\, P_{in} \right\rfloor * 3.78 \qquad \text{equation 2}$$

Where $F_{biosolids}$ = mass flux of biosolids, kg/yr
Q_{in},Q_{out} = monthly influent and effluent values in million gallons (MGD)/month.
P_{in}, P_{out} = monthly P concentrations, in mg/L

For the Albert Lea case, the influent P flux was 44,415 kg/yr, the effluent was 28,245 kg/yr, and the biosolids production was 15,870 kg/year; and P removal was 36%.

For many plants, one can verify the P flux to biosolids independently, using biosolids data on dry weight produced and P content (%). In 2010, Albert Lea produced 472 dry tons (429,091 kg) with an average P content of 2.98%, yielding P flux of 12,787 kg, about 10% less than the value calculated by difference (equation 2).

Effluent is most likely transported out of the watershed via a stream or river, but some portion may be recycled. Common uses of recycled wastewater include irrigation of non-edible crops (e.g., alfalfa, soybeans, or feed corn) and urban landscapes (e.g, parks and golf courses). The user specifies a percentage of effluent that is recycled to agriculture (outside the city) in cell B66.

Finally, some industries can be major sources of P to wastewater, especially food processing industries. In the City of Albert Lea, we estimated the combined P input from industries by subtracting household P inputs (calculated as described above) from the total P input to the Albert Lea wastewater treatment plant. Flow volumes for residential and commercial sewage was calculated by subtracting total industrial flows from total inflow to the wastewater treatment plant, (both measured by the City of Albert Lea). This revealed an industrial source of 22,248kg P/yr, about 50% of the total P input to the wastewater plant. The P balance for industries is treated in the next section.

Table 2. P balance for the Albert Lea Wastewater Treatment Plant. Data are from the Albert Lea Public Works Department in 2009.

	Total	Industrial	Residential & commercial	% res. & comm.	% industrial
Flow, MG/yr	1,342	135	1,208	90	10
BOD, kg/yr	1,926,489	559,514	1,366,976	71	29
P load, kg/yr	44,115	21,867	22,248	50	50
Calculated [P] mg/L		43	5		

Industrial Processes

Industrial processes can be a major component of a city's P balance. This is particularly true in a city like Albert Lea, which is home to several major food processing facilities. Developing P balances for industries within a watershed would nearly always involve conducting a survey of each industry. In this study we visited three food processing industries in Albert Lea. Information needed to compile a P balance include:

1. Annual quantities of unprocessed foods entering the plant. Plant managers generally have this information. To gain this information, we found it helpful to contact plant managers well before the actual survey to schedule a meeting, and then to provide them with the survey form soon before the visit, to give them time to find various pieces of information for their plants. We have provided a survey form (attached to this document) for users who want to conduct their own surveys.

2. The P content of each type of raw product. An excellent database for many raw foods is the USDA's Food Composition Database (http://fnic.nal.usda.gov/food-composition), which includes the P content (mg/kg) for nearly every type of food that can be eaten. For example, if a user entered "raw potato", he or she would like find a page titled "11353, Potatoes, russet, flesh and skin, raw", which have a P content of 41 mg/100 g" and could then readily find similar pages for "red potatoes", "white potatoes", etc. One could also find values for the skinned product, and by difference, have an estimate of the P content of the skin, which may be wasted. This data source was helpful in developing P balances for two of the food processing facilities in Albert Lea.

3. P in processing chemicals. A second type of P flux that occurs in many food processing facilities is the use of phosphate-containing chemicals, including cleansers for commercial food preparation surfaces. We found that plant managers had a fairly good idea of how much of each type of product they were using, but not necessarily their P contents. We were able to determine the P content of most of them, either from their molecular composition, or, for proprietary products, from published information on P contents. Some of these are summarized in Table 3.

Table 3. Some common industrial cleansers and processing agents used in food processing, showing P contents.

Product	P content,
Trisodium phosphate (TSP)	18%
Hexameta phosphate	5.0%
Disodium phosphate	9.6%
Phosphoric acid, 25%	7.9% (0.35 kg P/gal)
Dipotasium phosophate	18%
Quorum Pink	
Quorum Red	233 g P/gallon concentrate

4. <u>P in animal meat and bones.</u> For animal processing, developing a P balance is difficult, because it has to take into consideration the loss of body parts during slaughter and processing. Because most of the P in animals (~ 80% for hogs) is in the bones, the P content at various stages of production is very sensitive to the % bone remaining at various stages of processing. The P content of any part of an animal can therefore be estimated as:

$$P, \% = [P\%_{bones}\, M_{bones} - P\%_{meat} M_{meat}] \div [M_{meat} + M_{bones}] \text{ equation 3}$$

The table below illustrates this type of calculation to estimate the overall P content of a pig on the hoof, a carcass, and several major products. Hence, if the quantity of products were known, this could be translated into quantities of P.

Table 4. P content of various stages of butchering a hog. Data on bone percentages from (Ockerman and Hansen 2000); P content of meats from the USDA's Nutrient Database.

Portion of animal	% bone	P content of meat, %	Overall P content
On the hoof	12	0.15	0.67
Carcass	11	0.12	0.60
Ham, bone in	25	0.23	1.30
Picnic, bone in	24	0.20	1.23
Boston butt, bone in	22.6	0.19	1.16
Rib	39.5	0.20	1.90

5. <u>Quantities of by-products</u>. Many food processing plants and biofuels plants produce by-products that are rich in P. An example is bones from meat processing, which are sent to rendering plants to produce meat and bone meal and other products. Some other examples include use of vegetable trimmings as a feedstock

for hog feed, the use of distiller's grain from ethanol production in animal feed, and the use of eggshells in ceramics.

6. Production of solid wastes. These plants also produce wastes that are not utilized. Some materials may be "waste" in one plant, if there is no market, but a valuable by-product in another, where there is a market. Some wastes may be used indirectly, first composted and then recycled.

7. Disposal of liquid wastes. The P loading to sewers from food processing industries is probably a small fraction of the P in either raw foods entering the plant or the sum of processed foods and solid waste leaving the plant, so sewage P flows could not be accurately calculated "by difference". The only way to determine sewage P fluxes accurately is by direct measurement of effluents. This may be done as part of mandated pre-treatment programs, especially if the sewage treatment plant receiving these wastes has a P limitation in their NPDES permit. If so, the best local source of data would be the local wastewater treatment plant.

The Urban P Balance Calculator includes only a summary template to account for various P fluxes for industries (cells B44-B50). If industries with substantial P fluxes were present in a watershed, a user would have to visit each plant, learn about the quantities of materials being used, produced, and wasted, compute the P fluxes in each; then summarize total industrial P fluxes and enter the summary numbers into the Calculator. Table 5, below (extracted from the accompanying report *Phosphorus Balances for the Albert Lea Region*), summarizes the industrial P balances for the three major industrial facilities operating in Albert Lea in 2011.

Table 5. Summary of industrial P balances for Albert Lea, in kg P/yr.

	Merrick's	Mrs. Gerry's	Select Foods	Total industrial
Inputs				
Raw food products	14,871	5,321	1,750,036	1,770,228
Cleansers and chemicals	3,691	30.8		
Outputs				
Food products	14,838	4,798	19,636	39,272
Chemicals	3,691	31	0	3,722
By-products	16	0	1,617,082	1,617,098
Solid waste	16	478	0	494

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Summary - engineered system.
The spreadsheet calculator computes the overall P balance and then summarizes inputs (human and pet food, household chemicals, industrial raw materials, etc.), deliberate exports (food products, industrial by-products, and biosolids), export of solid wastes (e.g., transport to landfills outside the study area), and inadvertent exports (P to streams, rivers, and lakes). Accumulation occurs if food wastes are deposited to landfills within the urban system, or if there are septic systems within the city limits.

SUBMODEL FOR URBAN LANDSCAPES

The urban landscape submodel includes the urban system outside the fully engineered system – the part of the city that we see – residential lawns, parks, roads, etc.

P Inputs to Urban Landscapes

P inputs to urban landscapes include atmospheric deposition, lawn fertilizer, pet wastes, polyphosphates used in water treatment. Outputs include stormwater and exportation of landscape wastes and pet wastes. These are summarized in the "Urban Landscape" worksheet of the Urban Spreadsheet Calculator.

<u>Atmospheric deposition.</u> Atmospheric deposition of P occurs from both precipitation (wet deposition) and through deposition of P-containing particles (dry deposition). The Urban Spreadsheet Calculator uses values of wet and dry deposition compiled by Barr (2007, Tables 5 and 6) for each major watershed in Minnesota. The user can extract these for the specific region being modeled and enter the appropriate values into the Urban Spreadsheet Calculator (cells B19 and B20 of the Urban Landscape worksheet).

<u>Lawn fertilizer.</u> Before the Minnesota P fertilizer law was passed in 2003, lawn fertilizer would have been the major P input to urban vegetated surfaces (lawns; parks). Although some P fertilizer is still used in gardens and for "starter" turf fertilizers, the use of P fertilizers within urban areas has declined greatly. From 2003 (before passage of the law), 292 tons of lawn P fertilizer were sold; this had declined to 151 tons by 2006, just a year after its implementation (MDA 2007). Presumably the use of lawn P fertilizer has declined further since then. Hence, we assumed an input of "0" in cell B32.

<u>Pet waste.</u> For pets, what goes in comes out. Although pet food is generally consumed inside residences, excretion, at least for dogs, usually (hopefully!) occurs outside. A default value of 0.3 kg P/household is entered (Fissore et al., 2010), and the calculation proceeds by assuming that excretion equals food consumption. The urine fraction of dog excretion (25% of the total; (Wood et al. 2004)) remains on the lawn and the remaining 75% can be transferred from lawns to residential waste if dog owners collect the solid feces and move them to garbage cans. The default value for "pooper scooping" is 60%, (cell B23) based on a single study (the only one we could find) in Rhode Island (RDEQ 2003). This information is used to calculate the

total mass of P that remains on the lawn (cell B23) or removed from the urban landscape (cell B24); the latter is transferred to solid waste in the Engineered System sheet.

Irrigation P contribution. Polyphosphates are often added to municipal water supplies to reduce pipe corrosion (therefore reduce levels of lead and copper in water). This source of P enters urban landscapes when municipal water is used for landscape irrigation. This flux is calculated in the Urban Landscape page is the product of P concentration and total irrigation volume. The use of polyphospahtes for water supplies is tracked by the Minnesota Department of Health. Local water treatment plants could also readily supply this information. These data are generally presented "as PO4"; if so, the user would need to convert this to concentration "as P" by multiplying by 0.43. Irrigation volume can be estimated for a city's water treatment plant (or plants) from water production volumes throughout the year. Interior water use is fairly constant throughout the year, so this can be determined as the average of water use in months where there is no irrigation. In Minnesota, this would include the period October-April. The monthly value for interior water use can then be subtracted from annual water use to estimate outdoor (most irrigation) use. This calculation should be done for total water production. This process is illustrated with water production data from the city of Eden Prairie, Minnesota. Baseline (interior) water use is about 5 million gallons per day (MGD). This baseline can then be subtracted from total water production, month-by-month, to estimate irrigation volume; these volumes can then be summed to estimate total annual irrigation volume. For Eden Prairie, the annual interior water use was 61 million gallons and the annual irrigation water use was 28 million gallons, for a total of 89 million gallons. The user would then divide the irrigation volume by the service population to yield a per capita irrigation volume, which is entered into the Urban Landscape sheet. See cells B28-B30 on the Urban Landscape page.

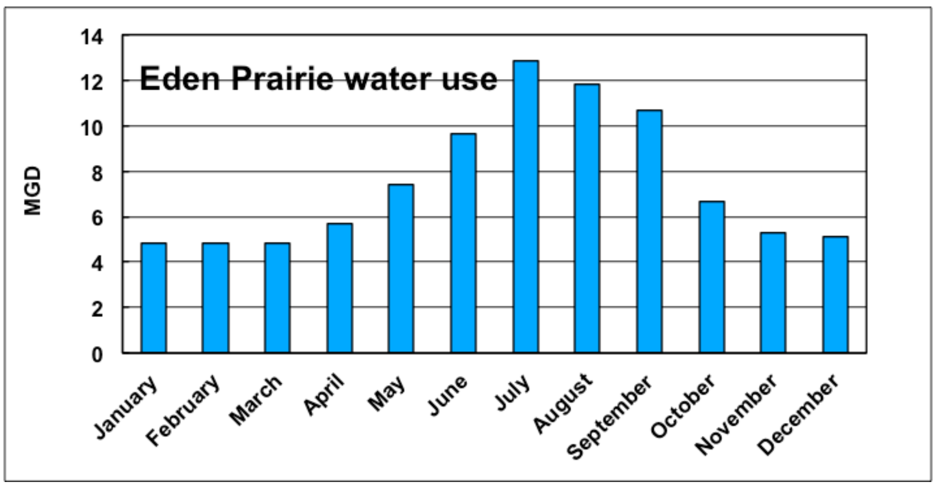


Figure 2. Water production for the city of Eden Prairie, Minnesota.

P Outputs from Urban Landscapes
P is exported from urban landscapes in two major waters: stormwater runoff and export of landscape vegetation wastes.

Stormwater. Some P entering urban landscapes is exported via stormwater conveyances, which drain to streams, rivers, or lakes. The Urban Landscape Calculator requires a single input value for the flux (loading) of P in urban stormwater. The default value, 0.5 kg/ha-yr (cell B44) is the average yield from six urban watersheds in the Capital Region Watershed District, which comprise most of St. Paul and a few surrounding suburban communities (Janke et al. 2013a). Cities that are part of the Municipal Separate Storm Sewer System (MS4) program may have ongoing monitoring programs with sufficient data to allow users to calculate site-specific P export loadings. Cities lying in watersheds with impaired waters downstream might also have completed Total Daily Maximum Load (TMDL) studies that include modeled P loadings. The Urban Landscape page allows users to insert their own stormwater P loads, which then replace the default value.

Landscape waste. Urban vegetated landscapes often yield landscape wastes that need to be removed. For residential households, the default value in the Urban Landscape sheet is 0.1 kg P/household/yr (Fissore et al. 2011, in cell B5). Landscape waste is often composted within city limits and may be either returned to urban landscapes (generally transported by citizens in their own vehicles) or may be exported to agricultural fields. Cell B53 asks for the percentage of landscape waste that is recycled within the city; the rest is presumed to be exported to agriculture.

Dog feces. The Urban P Balance Calculator includes algorithms for transferring dog food to lawns (100% is transferred, on the expectation by most owners that dogs defecate outside); and from the lawn back to the engineered household system. Briefly, the amount of dog feces transferred to household solid waste is the amount of excretion (urine + feces), minus the amount P of urine, times the percentage of dog waste that is picked up. This is a “transfer” of P from the landscape system to the engineered system.

P Accumulation
P accumulation (cell B63) is calculated as the difference between total P input and total P export (deliberate + stormwater). This includes recycled compost. Accumulation occurs mainly in soils within an urban landscape (Fissore et al. 2011). If the input of P exceeds exports, P must accumulate in urban landscapes. This increases the soil test P (STP). If exports exceed inputs, there is negative accumulation, which means that P is lost from the soils. Under this circumstance, STP would decrease over time. Generally, increasing STP levels would eventually lead to increased stormwater P loads, whereas decreasing STP levels would lead to decreased stormwater P loads.

Summary
Key P inputs to urban landscapes in Minnesota are pet wastes, atmospheric deposition, and polyphosphates in drinking water. Stormwater P is a ubiquitous P export mechanism. Landscape wastes are most often composted, and the compost is either recycled back to urban landscapes or exported to agricultural landscapes. Pet waste that is picked up is transferred to the household engineered system, and may be exported indirectly, via solid waste from households

P accumulation can be either positive (inputs > exports) or negative (exports > inputs). Positive accumulation is generally accompanied by increasing soil test P (STP), which is associated with increasing stream P export. Negative accumulation (P outputs > P inputs) will generally result in decreasing STP levels, and an eventual decrease in stream P export.

USER NOTES
The Urban P Balance Calculator is an open-source, Excel-based spreadsheet calculator. It was designed to be transparent and readily modifiable by the user. There are two worksheets, one for the engineered urban system and one for the urban landscape system. Although we attempted to represent a wide variety of situations, we could not foresee all possible permutations of P fluxes. Hence, the user may find it necessary to add algorithms to represent novel situations. The open source structure facilitates modifications by the user.

It contains a number of default values; these cells are colored pink. The user can change these, but if the user wants to revert to the original value, he or she can refer to the values presented in the “comments” column.

There are also a number of cells for which the user *must* provide values; these are shaded in green.

The comments provide default values, information regarding calculations, etc. The right column provides references for the user.

Finally, the bottom rows are a check on the overall P balance, to be sure that there is closure. In the original form, the model was tested under various scenarios and “passed” but as the user alters the model, especially when adding new algorithms, the P balance check, it may not, which tells the user that there is an error.

Because the user can overwrite default values and add new algorithms, we strongly suggest that the user re-save the file with a new name. If numerous modifications are made over time, it may be wise to save each version with a new name, to keep track of revisions. This would be especially useful if the file is being modified by several individuals.

REFERENCES

Baker, L., 2011. Can P conservation help to prevent the brown devolution? Chemosphere **84** 779-784.

Barr. 2007. Detailed Assessment of Phosphorus Sources to Minnesota Watersheds - Atmospheric Deposition: 2007 Update. Minnesota Pollution Control Agency, St. Paul.

Fissore, C., L. Baker, S. Hobbie, J. King, J. McFadden, K. Nelson, and I. Jakobsdottir. 2011. Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis–Saint Paul, Minnesota, urban region. Ecological Applications **2**:619-639.

Fissore , C., S. E. Hobbie, J. Y. King, J. P. McFadden, K. C. Nelson, and L. A. Baker. 2012. The residential landscape: fluxes of elements and the role of household decisions. Urban Ecosystems **15**:1-18.

Janke, B. D., J. C. Finlay , S. E. Hobbie, L. A. Baker, R. W. Sterner , D. Niidgorski, and B. N. Wilson. 2013b. Contrasting influences of stormflow and baseflow pathways on nitrogen and. Biogeochemistry DOI 10.1007/s10533-013-9926-1.

Kantor, L. S., K. Lipton, A. Manchester, and V. Oliveira. 1997. Estimating and addressing America's food losses. FoodReview **20**.

Lowe, K. S., M. B. Tucholke, J. M. B. Tomaras, K. Conn, C. Hoppe, J. E. Drewes, J. E. McCray, and J. D. Munakata-Marr. 2009. Influent constituent characteristics of the modern waste stream from single sources. Water Environment Research Founation and the International Water Association.

Metcalf and Eddy. 1991. Wastewater Engineering: Treatment, Disposal, and Reuse. McGraw-Hill.

MDA. 2007. Report to the Minnesota Legislature: Effectiveness of the Minnesota Phosphorus Lawn Fertilizer Law. Minnesota Department of Agriculture, St. Paul.

Ockerman, H. W., and C. Hansen. 2000. Animal byproduct processsing and utilization. Technomic Publishing, Lancaster, PA.

RDEQ. 2003. Stormwater guidance: pollution prevention-animal waste. Rhode Island Department of Environmental Quality Providence, RI.

Reed, S. C., R. W. Crites, and E. J. Middlebrooks. 1995. Natural systems for waste management and treatment. McGraw-Hill, New York.

Wood, C., K. Cummins, C. Williams, and B. Wood. 2004. Impact of diet and age on element excretion from dogs. Comm. Soil Sci. Plant Anal **35**:1263-1270.

PART II: USERS GUIDE FOR AGRICULTURAL P BALANCE CALCULATOR

An Excel spreadsheet database was developed as a tool to quantify P imports to, transfers within and exports from a specified study location. The **Agricultural P Balance Calculator** tool will provide the most accurate results when used for study areas located within Minnesota or adjacent agricultural states. Reference values used as assumptions in the calculations were constructed based on regional crop and livestock management statistics taken from various reports by the USDA, National Animal Health Monitoring System, together with other regional databases and personal interviews with crop productionists and animal science experts. All assumptions are documented in an *Explanation and References* information box located along the far right side of each corresponding sheet.

GETTING STARTED

Upon opening the *Agricultural P Balance Calculator* tool, you will begin on the *Instructions* tab. On this worksheet you will find the information necessary to get started using the worksheets. Green cells signify that a user specified value should be entered. Red cells signify that an internal calculation will be made based on the user's value entered in the green cell. Each worksheet that has a "User Defined Input" field features a reminder listed in cells A1 and A2, as shown below.

Enter data here
Calculation

The Agricultural P Balance Calculator was designed to include Atmospheric P Deposition, Cropping Systems, Egg Layers, Broilers, Turkey, Beef, Dairy and Swine. To account for P imports and exports from each of these components, the Calculator includes multiple worksheets. These worksheets are discussed below, including an explanation of specific User Defined Input necessary for completing the P calculations. Each worksheet is password protected; the default password is **LIVESTOCK**. This is also noted on the Instructions tab.

WORKSHEET DESCRIPTION

Atmospheric P Deposition

Atmospheric deposition is a source of P from pollen, soils, forest fires and other anthropogenic sources to watersheds. The total study area is the only User Defined Input required on this worksheet and is used to calculate the total annual atmospheric P deposited in four different units: kilograms, Megagrams, pounds and tons.

During an average year it is assumed that precipitation contributes 0.198 kilograms P per hectare while dry sources (e.g. dust and soil particles, pollen) contribute an additional 0.270 kilograms P per hectare (Barr Engineering, 2007). Although contributing dry sources could be from within the actual watershed boundary, they may also be imported into the watershed. The total P import due to atmospheric deposition is then determined by applying the total wet and dry deposition yield to the total study area.

Whole Ag P Balance
Total P imports, exports and transfers generated from the individual livestock and cropping system worksheets are compiled within this worksheet to represent the whole agricultural P balance. There are no additional User Defined Input cells since the data is collected on other independent worksheets.

The agricultural system P balance can be calculated using the general equation of:

P Imports = Deliberate P Exports + Stream P Exports + P Storage [1]

Imports include any livestock, feed or supplements, and fertilizers brought into the watershed boundary. Deliberate exports include meat and dairy products, harvested crops not consumed as livestock feed, and livestock mortalities that are exported outside of the study area to composting facilities, landfills or rendering plants. Manure is considered a transfer rather than an export since it is applied onto the watershed cropland as P fertilizer.

The P use efficiency of the whole agricultural system is calculated using the following equation:

$$\text{Agricultural } P_{\text{efficiency}} = \frac{\text{Total P Exports}}{\text{Total P Imports}} \quad [2]$$

If the agricultural $P_{\text{efficiency}}$ is greater than 1, P exports are leaving the watershed at a mass greater than imported. Therefore, the watershed P storage and soil test P (STP) should decrease with time, eventually leading to declines in stream P due to reduced contributions from surface P runoff (Klatt et al., 2003, Ekholm et al., 2005; Sharpley et al., 2006). If the $P_{\text{efficiency}}$ is less than 1, the watershed is inefficiently utilizing P by importing more than is exported. This results in increased P storage and STP levels, which could lead to increases in stream P.

The total crop P exported is calculated by subtracting out the total P consumed as livestock feed from the total P produced as harvested crops within the study area. Fertilizer P imported is calculated by subtracting the manure P produced by livestock in the study area from the required P input to crops. Results summarizing the total mass of imports and exports are provided in four different units: kilograms, Megagrams, pounds and tons. The Agricultural $P_{\text{efficiency}}$ is provided at the bottom of the worksheet with and without applying the atmospheric deposition as an import.

Crop P Balance
Minnesota's primary production crops are included on the Crop P Balance worksheet. User Defined Input cells include the harvested acres, fertilizer application rate, cropland with applied fertilizer *(as a percent)*, manure application

rate, cropland with applied manure *(as a percent)*, and the average crop yield. The values that show up automatically on the worksheet are specific to Minnesota. If data was not available, other Midwest agricultural values were applied; all of the corresponding references are summarized in the *Explanation and References* information box on the worksheet.

Crop P removal efficiency is commonly used to explain nutrient efficiency. The P removal efficiency for each crop was calculated using the following equation (Dibb et al., 2003; Fixen, 2009):

$$\text{Crop } P_{\text{efficiency}} = \frac{\text{Crop P uptake}}{\text{Applied fertilizer+manure P}} \quad [3]$$

If the crop $P_{efficiency}$ is greater than 1, the soil P will likely decrease with time because crops are extracting P from the soil at a rate greater than it is being incorporated as fertilizer and manure. If the Crop $P_{efficiency}$ is less than 1, the soil P will likely increase due to inputs applied at a rate greater than they are being extracted, which can lead to increased P runoff.

For the agricultural system P balance, fertilizer is treated as an import into the system based on the difference between total P applied to cropland and manure P produced within the study area. Total area covered by each crop can be estimated for the study area using the National Agricultural Statistic Service Cropland Data Layer (USDA, 2011a) or through conducting surveys.

Fertilizer and manure application data, specific to the study area, could be compiled by conducting local farm surveys, consulting with local agricultural cooperatives or extension agents, or generalized based on the most recent Agricultural Resource Management Survey (ARMS) data available together with University of Minnesota extension data. The worksheet calculates the total fertilizer applied by multiplying the total harvested area by the percentage of cropland with applied fertilizer and the fertilizer application rate. Additionally, the worksheet contains estimates of dairy, swine and beef manure P, which are averaged to determine the average manure P applied to calculate the total mass of manure P applied within the study area. These percentages are protected, but can be altered by unprotecting the worksheet. Total manure P applied is calculated using the same approach as fertilizer P, by multiplying the total harvest acres by the percentage of cropland with applied manure and the manure application rate. It is important to remember to consider that planted area is not always consistent with harvest acres. If a large area receives fertilizer inputs and is not harvested, the insertion of an additional cell may need to be considered to capture the P storage.

The worksheet automatically calculates total crop P uptake by determining the dry matter yield and applying the percent P of dry matter for each crop as summarized by Ketterings and Czymmek (2007).

Feed Summary

The Feed Summary worksheet automatically calculates livestock feed imports. This worksheet should not be edited until the Crop P Balance and livestock worksheets are compiled. This worksheet summarizes all of the livestock feed information and excludes any feed ingredients that are imported into the study area, or require some processing prior to distribution to livestock (e.g. bakery by-products, soybean oil, milk replacer). The only User Defined Input cells include the formulas which sum the imported feed totals. Editing these cells will result in updated Feed Imports and Study Area Produced Feed values found within the Whole Ag P Balance worksheet.

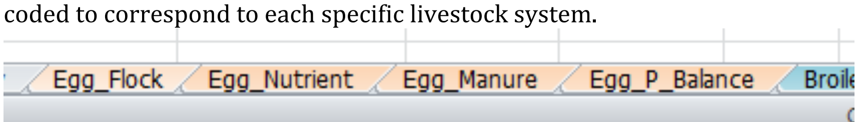
Livestock Worksheets

The P efficiency of each individual livestock production system is evaluated using the following equation:

$$\text{Livestock } P_{\text{efficiency}} = \frac{\text{Livestock Product}}{\text{P Consumption}} \qquad [4]$$

Livestock products include any egg, meat, dairy, or rendered mortality, while P consumption accounts for the P consumed in supplements and feed by the livestock. A livestock $P_{efficiency}$ close to 1 may be achieved by minimizing the manure P or rendering farm mortalities. The livestock efficiencies calculated by Eq. [4] will decrease during processing; however, the Calculator considers the P mass of the whole animal a livestock product exported from the study area to avoid quantifying processing losses, which would require additional surveys of individual processing facilities. In other words, the efficiency values calculated using these worksheets will be the maximum obtainable in that livestock system under the assumed management scenarios; efficiencies will decrease as the livestock is processed.

Each livestock system is broken up into a group of independent worksheets used to calculate the P efficiency of each system individually, which is also incorporated into the whole agricultural P balance. Each group of worksheets contains a flock or herd calculator, worksheet(s) used to calculate feed consumption based on nutritional requirements, manure calculation worksheet, and system P balance worksheet. The tab for each group of worksheets, as demonstrated below for the Egg Layers, is color coded to correspond to each specific livestock system.



The coordinating color coding scheme is illustrated below:

Egg Layer
Broiler
Turkey
Beef

Dairy
Swine

Manure
A separate Manure worksheet is used within each livestock system. For each system the P excreted as manure is first calculated using the University of Nebraska's Manure Nutrient and Land Requirement Estimator (Koelsch, 2006). The spreadsheets estimate excretion of nutrients and solids for each of the evaluated livestock systems based upon American Society of Agricultural and Biological Engineers Standard D384.2, Manure Production and Characteristics. Livestock management information including the size of the animal, daily feed intake, and dietary P composition was input into the manure estimator to calculate the daily P mass excreted at each phase in the animal's life cycle. These P values were extracted from the estimator and incorporated into the Agricultural P Calculator tool worksheets.

If the User determines that dietary or ration modifications should be made to any of the livestock systems, the User will need to download this external spreadsheet to estimate the daily mass of P produced per animal. When using the default dietary nutrient inputs provided within the Agricultural P Calculator tool, the total manure P produced is calculated automatically without any required User Defined Input fields. The total annual P mass from each livestock system is linked into the Whole Ag P Balance spreadsheet to calculate the total manure P produced within the study area and available as a crop nutrient. Although manure is applied to the agricultural crop fields within the study area as a P fertilizer, it is not factored into the livestock P efficiency ratio because it is a byproduct of livestock production and remains within the study area so is considered a nutrient transfer. Transfers are considered in the holistic system P balance through the reduction of imported P fertilizer.

Feed Composition and Nutrient Requirements
Nutrient requirements for beef cattle, dairy cattle, poultry and swine, published by the National Research Council (NRC), were used to verify adequate feed ration simulation. Diets vary based on the location of the livestock production because of the availability of varying feed sources. Since this Calculator was developed for Minnesota, soybean meal was selected as a primary protein supplement. Additionally, Dried Distillers Grain with Solubles (DDGS) was also incorporated as a feed source for each of the livestock groups. To model the most accurate and local feed ration, diets were established based on extension publications and interviews with University of Minnesota poultry, swine and cattle experts, and confirmed by local producers. These diets are compiled within the worksheets labeled Nutrient. The resulting recipes compiled within the Calculator were compared with the NRC dietary requirements to ensure that adequate nutrients were supplied. Within each Nutrient worksheet for each livestock system, the NRC requirements are highlighted as indicated below.

Nonphytate P requirement (NRC, 1994) (kg/week)
Nonphytate P requirement (NRC, 1994) (%)

The nutrient composition, specifically %P, of each feed source (i.e. corn, soybean meal, distillers grain) was also obtained from the NRC nutrient requirement references and input into the P balance spreadsheet. The rations listed within the Nutrient worksheets are linked to the Feed Composition worksheet to allow automatic updates of nutrient intake if feed rations are adjusted. It is important to remember that manual changes made to any of the Nutrient worksheets which result in a change in the P consumed will require a manual update to the Manure spreadsheet using the external Manure Nutrient and Land Requirement Estimator.

Each Nutrient spreadsheet follows the same outline with a slightly different set-up determined based upon the presentation of data available. For example, if the flock or herd consistently contains the same number of animals at each stage throughout the year, diet ingredients may be presented as kilograms per year versus kilograms per life stage (i.e. age group). All units are labeled and should be noted.

Toward the bottom of each Nutrient worksheet there is an annual summary table for each livestock system. Within each table the feed ingredients are totaled for each life stage and in most cases will be presented as a dry matter mass. As noted above, units will vary depending on the reference source. The columns located in the far right end of the table summarize the total annual herd or flock consumption as total feed mass and P mass. The P mass is the value that is linked to the PhosBalance worksheet, which will be discussed further below.

The swine system calculates the feed composition using its own Feed Composition Swine worksheet. It is not linked into the same Feed Composition worksheet as the other livestock systems because the diets are based on wet weight requiring an independent set of conversions. Additionally, the swine system has a SwineFeedCalculator worksheet which formulates the feed rations based on personal communication with Dr. Gerald Shurson, Animal Science Professor at the University of Minnesota, and through cooperation with local Minnesota hog producers. Additional information on the conversion calculations is provided in the *Explanation and References* box on the SwineFeedCalculator worksheet.

It is noted in the *Explanation and References* box of the Beef Feed worksheet that the diets were formulated using several in depth feed spreadsheets constructed by Alfredo DiConstanzo, Animal Science Professor with the University of Minnesota Beef Extension Team. The spreadsheets were constructed to represent both grass-fed and conventional beef systems. These five additional spreadsheets are included internally within the database, but are hidden since they provide background energy calculations based on daily growth and development needs. *If desired, they may be accessed by the User by unprotecting the workbook and choosing to unhide the sheets.* Both the conventional and the grass-fed systems were modeled by Dr.

DiConstanzo based on the required net energy to gain and maintain weight at monthly intervals. One feed system uses forage hay together with grazing for a total of 19 months, while the second also incorporated additional feed sources into the diet at the feeder stage, which follows approximately 7 months of forage feeding. The dairy steer calves that are imported into the watershed for beef production after birth are modeled to start feeding on milk replacer.

Herd/Flock Structure Worksheets
Each livestock system consists of a herd structure unique to that specific animal's reproduction and development rate, as well as individual farm management practices. Livestock management is constantly changing based on available resources and advancements in technology. In order to accurately model feed consumption, manure production, and mortality disposal throughout the life cycle, the herd structure for each livestock system was constructed based on regional management statistics taken from various reports by the USDA, National Animal Health Monitoring System, together with other regional databases and personal interviews with animal science experts. User Defined Inputs vary between each livestock system, each will be discussed below. The spreadsheets were constructed so that most of the User Defined Inputs are based on data commonly available through the National Agricultural Statistics Service (NASS), Quick Stats website (USDA, 2013). Values calculated on the herd or flock worksheets are used to automatically populate the livestock numbers found on the Nutrient, Manure and P Balance worksheets. Any assumption used to calculate the herd or flock is provided on the respective worksheet in the *Explanation and References* box. Further detail and elaboration on the herd and flock structures could be found in the complimenting agricultural system P balance journal article (Peterson et al., *In Progress*).

Egg Flock. To calculate the layer flock structure for edible egg production, the worksheet assumes the use of leghorn chickens as layers. The only User Defined Input required to estimate the flock structure is the total number of layers at a given time and the number of eggs per layer. These values are commonly available through the NASS, Quick Stats website (USDA, 2013). If a more specific egg production statistic is not available, the default egg production estimate is available in the *Explanation and References* box, as well as information regarding mortality rates, number of pullet flocks and breeding ratios.

The flock estimation calculates the breeding herd required to produce the egg layers, factoring into consideration the annual number of culled and deceased layers. The total number of eggs produced annually is also determined, which is considered a deliberate P export on the Egg P Balance worksheet.

Broiler Flock. The Broiler Flock worksheet calculates flock structure based on the annual number of broilers produced. This is a User Defined value commonly available through the NASS, Quick Stats website (USDA, 2013). The calculation factors in mortality and egg hatchability. It assumes a 50/50 slaughter rate of female and male broilers. The number of broilers produced and total mortalities are linked into the Broiler P Balance worksheet as deliberate P exports.

Turkey Flock. The Turkey Flock worksheet calculates flock structure based on the annual number of turkeys produced. This is a User Defined value commonly available through the NASS, Quick Stats website (USDA, 2013). The calculator does consider the number of toms and hens necessary to produce the poults that are raised for slaughter. The calculation factors in mortality and egg hatchability. To account for the reproduction herd, the User can verify if poults are hatched within the study area by typing YES into the specified entry location. By entering YES the number of toms and hens, *including replacements*, which are required to reproduce the number of young turkeys produced within the study area is calculated assuming. If YES is not entered into Cell C18, then it is assumed that poults are imported into the study area, and the formulas are automatically adjusted. These values are estimated using the references provided in the *Explanation and References* box on the worksheet. The number of turkeys produced, poults imported and total mortalities are linked into the Turkey P Balance worksheet as deliberate exports.

Beef Herd. The Beef Herd Structure worksheet calculates the herd structure based on the annual number of cows that calved, or total cows. As noted on the worksheet, only one of these two statistics is necessary to compute the corresponding herd, and typically these values can be found through the NASS, Quick Stats website (USDA, 2013). Additionally, the User may choose to define the number of grass-fed animals in the system; both the number of grass-fed males and females is highlighted in green as a User Defined option, but these values are not required to proceed with a calculation. The total number of male and female conventional feeders is adjusted based on whether values are entered into the grass-fed cells. If grass-fed cattle are considered, their nutrient intake is modeled separately from the conventionally fed livestock. This alters the lifespan of the livestock in the system since it takes grass-fed cattle longer to reach slaughter weight; conventionally raised cattle are slaughtered at approximately 16 months while grass-fed are approximately 19 months.

The herd structure also considers the number of dairy steer calves that are imported into the system after birth for beef production and this number is automatically populated from the Dairy Herd worksheet. These cattle are typically Holsteins and are modeled to exit the herd at a lighter weight (1212 lbs) than conventional beef steer breeds (1354 lbs), but remain within the herd for the same 16 month duration.

The required number of bulls within the system was assumed to be approximately one mature bull to impregnate 24 heifers or cows (USDA, 2008; 2009). Since portions of the information used for the beef herd were compiled from research previously generated by Alfredo DiConstanzo with the University of Minnesota Beef Extension Team, there are several hidden rows located at the top of this worksheet. These values are hidden to simplify the worksheet; however, the User may choose to unhide and evaluate these numbers. The hidden fields quantify the assumed calving, weaning and replacement percentages. For example, successful calving occurs in 93.1% of the cows, while 87.4% of these calves make it through weaning and are then assumed to remain within the herd through the feeder stage (Nordquist, 2012). Approximately 6.7% of mortalities are pre-weaning and 1.4% are post-weaning. The total number of feeders, culled beef heifers and total mortalities are linked into the Beef P Balance worksheet as deliberate P exports, whereas the dairy steers imported into the herd are considered P imports. Additional references for the beef herd structure can be found in the *Explanation and References* box on the worksheet.

Dairy Herd. The Dairy Herd worksheet calculates the herd structure based on the total number of cows and heifers *or* the total number of milking cows. Both of these values are typically available through the NASS, Quick Stats website (USDA, 2013). If the total number of milking cows is know, that value is entered into cell C7. If the total herd size is knows, that value is entered in cell C6. For a dairy herd, it is important for the User to understand that the term cow refers to a mature female which has already calved, whereas a heifer is a female which has not yet calved. A first-calf heifer has calved once. Details on the calculations used to determine the required number of replacement heifers and first-calf heifers are discussed in Peterson et al. (in progress), and were compiled using Wattiaux and McDullough (1994). Based on a 15 month calving interval and an approximate 9 month pregnancy, it is estimated that 25% of the total cow & heifer herd is dry, *or not lactating*, at a given time (MNDHIA, 2012). These specific herd values are especially important for the dairy system because the nutrient consumption and manure production varies depending on the life cycle stage of the animal. Lactating cows requires a much higher quantity of P in their diet compared to a dry cow. The number of farms is a User Defined Input value and is used to calculate the number of bulls within the system. Although artificial insemination (AI) is commonly used to impregnate the dairy heifer and cows, approximately 47% of productions keep at least one bull in the herd to help with any unsuccessful AI pregnancies. The User should enter into Cell F13 the total number of dairy farms within the study area, and the total number of bulls will automatically be calculated using USDA (2008, 2009) statistics. Any male calves birthed into the system are treated as an export from the dairy system and imported into the beef herd; this value is automatically transferred to the DairyPBalance and BeefPBalance worksheets. Additional references for the dairy herd structure can be found in the *Explanation and References* box on the worksheet.

Hog Herd. The Hog Herd Structure worksheet calculates the herd structure based on the total number of breeding sows, average liter size, and number of farms. Typically these values can be found through the NASS, Quick Stats website (USDA, 2013). As noted on the worksheet, if the total annual pig crop is known but the total number of breeding sows is not, the User may override the formula used to calculate the pig crop number to instead calculate the total number of required breeding sows. By inserting a value into cell C9, the formulas are reversed and a calculated number of total breeding sows will appear in cell C6. The User will then need to type the resulting number into cell B6. The number of farms is needed to calculate the number of boars within the system. The average piglet litter size in 2010 for Minnesota was 10, so this number should be used as the Default unless the User has a regional or farm specific value that is preferred (USDA, 2013). Although AI is commonly used to impregnate the breeding sows, approximately 35% of productions keep at least one boar in the herd to help with any unsuccessful AI pregnancies. If there are piglets that are imported into the system rather than bred, the User may record that value in cell B14 and then choose to edit the pig crop and total breeding sows based on that inserted value There are a number of references for the statistics used to calculate the hog herd structure listed and explained in the *Explanation and References* box on the worksheet. The total number of slaughtered animals, culled sows and total mortalities are linked into the Hog P Balance worksheet as deliberate P exports, whereas any imported piglets would be considered P imports.

Livestock P Balance Worksheets
Each flock or herd has a unique system P balance worksheet associated with the herd structure, feed consumption and manure production. Each of these worksheets is constructed to automatically populate and transfer values to the Whole_Ag_P_Balance worksheet. These individual system P balance worksheets allow the User to identify the P efficiency for each individual livestock system and to identify the associated P balance error.

Each of these worksheets list the *Total P Feed Consumption* as the first row of the P Balance table, followed by the total P import by *Supplements*. Although the P supplied as a supplement is listed separately on the table, this value is also already included in the *Total P Feed Consumption* value. Supplements were listed separately in each system P balance worksheet to provide an estimate of what quantity of P was added to the bird or animals diet.

Transfers within the systems include the manure produced, which is assumed to be land applied within the system boundary, *and/or* any carcass that is composted or landfilled within the system boundary. If a study area exports the manure or the landfilled or composted carcasses, the worksheets should be edited to reconsider these values as exports. The manure production values are automatically tabulated and transferred to the Whole Ag P Balance worksheet to calculate the total fertilizer P that is imported into the whole system.

Egg Flock. Imports automatically applied to the EggPBalance worksheet include the feed P consumed by the flock and the equivalent P imported as breeding hens or cockerels. The corresponding P composition assumptions for the hens and cockerels are provided on the worksheet; these values vary depending on the age of the bird or stage/use of the egg. These values are used to quantify both the P imports and exports. Deliberate P exports from the system include the P from the eggs produced, rendered products and processed birds. Further description on these items is provided in the *Explanation and References* box on the worksheet.

Broiler Flock. Imports automatically applied to the BroilerPBalance worksheet include the feed P consumed by the flock and the equivalent P imported as eggs that were imported into the hatchery. The corresponding P composition assumptions for the broilers and eggs are provided on the worksheet; these values vary depending on the age of the bird or development stage of the egg. These values are used to quantify both the P imports and exports. Deliberate exports from the system include the P from the broiler chickens produced and any rendered products. Rendered products are assumed to be any young chicken mortality and unhatched eggs.

Turkey Flock. Imports automatically applied to the TurkeyPBalance worksheet include the feed P consumed by the flock and the equivalent P imported as poults or breeders. The corresponding P composition assumptions for the turkey, poults and eggs are provided on the worksheet; these values vary depending on the age of the bird *or* development stage of the egg. These values are used to quantify both the P imports and exports. Deliberate exports from the system include the P from the total number of turkeys produced and any rendered products. It is assumed that annually 15 eggs per breeder do not hatch, therefore these whole eggs and the shells from the hatched eggs are considered rendered products (USDA, 2011b). Turkey mortalities are generally disposed of through trash pick-up and are treated as a P transfer; if it is verified that the trash hauler disposes of them outside of the study area, this value should instead be edited to reflect a P export (USDA, 2006). Further description of turkey P assumptions is provided in the *Explanation and References* box on the worksheet.

Beef Herd. Imports automatically applied to the BeefPBalance worksheet include the feed P consumed by the herd and the equivalent P imported as dairy beef calves. Male calves born into a dairy system are typically exported to beef production herds. Therefore, they are treated as an import into the beef system. These cattle are typically Holsteins and are modeled at a lighter weight than conventional beef steer breeds. Over 90% of cattle mortalities are composted or landfilled and are treated as a system transfer. Deliberate exports include cattle exported for slaughter or rendering. Further description of beef P assumptions is provided in the *Explanation and References* box on the worksheet.

Dairy Herd. Imports automatically applied to the DairyPBalance worksheet include the feed P consumed by the herd. Deliberate exports include P in the produced milk and P composition of the dry cows and male calves exported to the beef system for slaughter. The milk output is calculated on this worksheet using a default of 80 pounds of milk per day, for a 305 day cycle. The User may over-ride these default values by entering the known milk output into Cells B19 and C19.

Hog Herd. Imports automatically applied to the SwinePBalance worksheet include the feed P consumed by the herd and any piglets input into the herd. Deliberate exports include hogs exported for slaughter or rendering. In addition to manure, 40% of hog mortalities are treated as a system transfer since they are composted or landfilled. If these mortalities actually leave the system, their values should be edited to reflect an export rather than a system transfer.

REFERENCES

Barr Engineering Company. 2007. Technical memorandum to the Minnesota Pollution Control Agency: Detailed Assessment of Phosphorus Sources to Minnesota Watersheds – Atmospheric Deposition. June 29, 2007. Minneapolis, MN.

Dibb, D.W., P.W. Fixen, and M.D. Stauffer. 2003. Fertilizer use efficiency: The North American experience. Fertilizer Demand Meeting of the International Fertilizer Industry Association (IFA) Agriculture Committee, Philadelphia, PA .26 May 2003.

Ekholm, P., E. Turtola, J. Gronroos, P. Seuri, and K. Ylivainio. 2005. Phosphorus loss from different farming systems estimated from soil surface phosphorus balance. Agriculture, Ecosystems and Environ. **110**: 266-278.

Fixen, P.E. 2009. Phosphorus: worldwide supplied and efficiency. Manitoba Agronomists Conference, Winnipeg, Manitoba. 16 Dec. 2009.

Ketterings, Q., and K. Czymmek. 2007. Removal of phosphorus by field crops. Agronomy Fact Sheet Series Fact Sheet 28, Cornell University Cooperative Extension, Ithaca, NY.

Klatt, J.G., A.P. Mallarino, J.A. Downing, J.A. Kopaska, and D.J. Wittry. 2003. Soil phosphorus, management practices, and their relationship to phosphorus delivery in the Iowa Clear Lake agricultural watershed. J. Environ. Qual., **32**:2140-2149.

Koelsch, R.K. 2006. Manure nutrient and land requirment estimator. University of Nebraska, Lincoln. Available at: http://water.unl.edu/web/manure/software

Minnesota Dairy Herd Improvement Association (MnDHIA). 2011. Scorecard for 2011. http://www.mndhia.org/ (accessed 17 March 2014).

National Research Council (NRC). 2001. Nutrient requirements of dairy cattle 7th ed. National Academy Press, Washington, D.C.

Nordquist, D. 2012. FINBIN report on Minnesota farm finances. Center for Farm Financial Management, Univ. of Minnesota, St.Paul, MN.

Peterson, H.M., L.A. Baker, J.S. Ulrich, D. Bruening, J.L. Nieber, and B.N. Wilson. *In Progress.* Agricultural system phosphorus balance for addressing watershed TMDL goals.

Sharpley, A. N., T. Daniel, G. Gibson, L. Bundy, M. Cabrera, T. Sims, R. Stevens, J. Lemunyon, P. Kleinman, and R. Parry. 2006. Best management practices to minimize agricultural phosphorus impacts on water quality. ARS-163. USDA-ARS, University Park, PA.

USDA. 2006. Poultry 2004 Part III: Reference of management practices in live-poultry markets in the United States, 2004. NAHMS #N44.0406. USDA-APHIS-VS, CEAH. Fort Collins, CO.

USDA. 2008. Dairy 2007, Part II: Changes in the U.S. dairy cattle industry, 1991–2007. #N481.0308. USDA-APHIS-VS, CEAH. Fort Collins, CO.

USDA. 2009. Beef 2007–08, Part III: Changes in the U.S. beef cow-calf industry, 1993–2008. #518.0509. USDA:APHIS:VS, CEAH. Fort Collins, CO.
USDA. 2011a. National Agricultural Statistics Service, 2010 Minnesota Cropland Data Layer (CDL). Washington, D.C.
USDA. 2011b. Poultry 2010 Structure of the U.S. poultry industry, 2010. NAHMS #583.1211. Fort Collins, CO.
USDA. 2013. National Agricultural Statistics Service (NASS), Quick Stats. http://quickstats.nass.usda.gov/ (accessed 9 May 2013).
Wattiaux M.A., and D. McCullough. 1994. Factors affecting size and productivity of the dairy replacement herd. In: Babcock Institute for International Dairy Research and Development, editor, Dairy essentials: nutrition and feeding, reproduction and selection, lactation and milking, raising dairy heifers. University of Wisconsin, Madison, WI. p. 101-104.

SECTION III. BIOGEOCHEMICAL DIAGNOSTIC TOOLS

INTRODUCTION

The watershed P balance tools developed in the previous sections provide insights regarding the overall P balance of a watershed and are especially useful for identifying opportunities to improve P use efficiencies in both urban and agricultural settings.

Further insights towards improving the selection of BMPs can be provided by more detailed examination of the hydrology and water chemistry of streams, agricultural ditches, and individual tile drains. Very commonly, BMPs are installed based on their capacity to trap particles. The common implicit assumption is that P is bound to particles, hence trapping particles traps P. A great deal of accumulated evidence suggests that soluble P can be an important, and even the dominant form of P in many situations. In agriculture, these include sandy or highly organic soils, long-term accumulation of fertilizer or manure P in soils, and the presence of tile drainage (Sims et al. 1998). For example, (Gentry et al. 2007) found that soluble P loads were often > 50% of total P (TP) loads in tile drained agricultural watersheds in Illinois. Soluble P may also dominate P loads during snowmelt periods (Hansen et al. 2000). Aside from agriculture, subsurface movement of phosphate also occurs from septic system leach fields(Richardson 1985.), and a phosphate-rich plume was observed to travel more than a quarter-mile from an abandoned sewage pond to Mill Pond, Connecticut (McCobb et al. 2003). Soluble P also comprised about one-third of the stormwater TP loads in the Twin Cities (Brezonik and Stadelmann 2002) and dominated TP loads in a year-round study of runoff from experimental lawns (Bierman et al. 2010). In summary, soluble P is often an important and sometimes a dominant form of P in both agricultural and urban runoff, and can also travel through the subsurface.

Hence, watershed managers must consider the form and source of P while planning implementation of BMPs. This section outlines some “biogeochemical diagnostics” that watershed managers could employ for this task. These include:

1. More detailed analysis of routine monitoring data that is usually done, to gain insights regarding sources of P under various hydrologic conditions.

2. Additional analyses that are not routinely included in monitoring programs for agricultural streams, but which may provide additional insights regarding the behavior of P.

3. Specific diagnostic studies, such as synoptic studies of many sites across the landscape, or storm analysis for a particular site.

Taken together, these diagnostic tools can provide considerable insights regarding the sources of water and nutrients at a particular site, and thereby help to design effective and cost efficient BMPs

Diagnostic Analysis of Fixed-Site Monitoring Data

Many agricultural watersheds are now gauged to measure flow and have established water quality monitoring programs. In many situations, however, the main use of this data is limited to making calculations of the mass loadings of sediment and nutrients. However, these databases also contain a wealth of data that could be more fully used to understand nutrient dynamics and guide implementation of best management practices (BMPs).

This section illustrates how fixed-site monitoring data can be used to understand P dynamics and guide BMP implementation in three agricultural streams in Shell Rock River Watershed District (SRRWSD). Data presented here are for three key agricultural watersheds, Bancroft Creek, Peter Lund Creek, and Wedge Creek. All three are predominantly cropland (76% - 84% of total watershed area) and the main crops in all three watersheds are corn and soybean (Table 1).

Table 1. Characteristics of the agricultural case study watersheds.

	Bancroft Creek	Peter Lund Creek	Wedge Creek
Total watershed area, ha	8,782	7,597	8,978
Corn + soybeans, %	70.9	81.6	73.6
Other crops, %	5.3	2.0	4.5
Total cropland, %	76	84	78
Developed (low/medium/high)	2.0	1.3	1.2
Developed open+barren	10.2	8.2	8.5
Forest	2.7	1.1	2.5
Grassland	7.7	5.1	7.1
Lakes and wetlands	1.2	0.8	2.7

Loading analysis

As a first step, annual averages for the period 2009-2011 were calculated for water yields, TP fluxes, and TP yields, broken down into ortho-P and particulate P, the latter calculated as TP – ortho-P. "Ortho-P" is approximately equal to "soluble P". Table 2 shows that ortho-P is the dominant form of P in streams exiting all three watersheds, accounting for 61% to 74% of TP.

Table 2. Fluxes of water and phosphorus among the three case study watersheds, 2009-2011, as annual averages.

	TP flux (kg/yr)	TP yield kg/ha/yr	Part. P, %	Ortho P, %	Water yield (cm/yr)	Runoff ratio
Bancroft Creek	5411	0.62	26	74	30	0.37
Wedge Creek	7904	0.88	39	61	33	0.39
Peter Lund Creek	5250	0.69	36	64	24	0.29

Watershed characteristics that would tend to promote dominance of ortho-P include (1) extensive tile drainage, (2) relatively flat topography, and (3) extensive buffer strips.

Relationship between P forms and flow
Plots of flow vs. TP and ortho-P (Figure 1, top) show that ortho-P dominates across flow regimes, even during peak flows. In fact, the dominance of ortho-P increases with flow in Bancroft and Wedge Creeks (Figure 1, middle). In Peter Lund Creek, ortho-P is consistently > 50% of TP.

As with streams where particulate P dominates, peak TP loadings account for a large percentage of total TP loadings. Table 3 shows the sum of daily TP loads on days when both TP and ortho-P were measured. For all three streams maximum daily TP loads were 33% to 50% of the summed TP loads for all measurement dates. Peak daily ortho-P loads were about one-third of the summed TP loads. Equally important with respect to informing implementation of BMPs, ortho-P comprised 67-97% of TP on the peak TP loading days.

Table 3. Analysis of peak P loading days in relation to the sum of daily P loadings on days when P concentrations were measured.

	# of sample pairs	Sum of TP loads on sampled days, kg	Peak daily TP load, kg/day (% of sum)	Peak daily ortho-P load, kg/day (% of sum)	% ortho-P on peak TP loading day
Bancroft Creek	46	1284	509 (33%)	493 (38%)	97
Peter Lund Creek	17	366	165 (45%)	110 (30%)	67
Wedge Creek	39	2194	1104 (50%)	798 (36%)	72