Relative Effects of Land Use and Near-Stream Chemistry on Phosphorus in an Urban Stream

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ABSTRACT

Elevated levels of P in urban streams can pose significant water quality problems. Sources of P in urban streams, however, are difficult to identify. It is important to recognize both natural and anthropogenic sources of P. We investigated near-stream chemistry and land use factors on stream water P in the urbanizing Johnson Creek watershed in Portland, OR, USA. We sampled stream water and shallow groundwater soluble reactive P (SRP) and total P (TP) and estimated P flux at 13 sites along the main stem of Johnson Creek, with eight sites in urban land use areas and five sites in nonurban land use areas. At each site, we sampled the A and B horizons, measuring soil pH, water-soluble P, acid-soluble P, base-soluble P, total P, Fe, and Al. We found continuous input of P to the stream water via shallow groundwater throughout the Johnson Creek watershed. The shallow groundwater P concentrations were correlated with stream water P within the nonurban area; however, this correlation was not found in the urban area, suggesting that other factors in the urban area masked the relationship between groundwater P and stream water P. Aluminum and Fe concentrations were inversely correlated with shallow groundwater P, suggesting that greater P adsorption to Al and Fe oxides in the nonurban area reduced availability of shallow groundwater P. Using stepwise multiple regression analysis, however, we concluded that while riparian soil chemistry was related to stream water P, land use patterns had a more significant relationship with stream water P concentrations in this urbanizing system.

Elevated level of P in urban streams caused by nonpoint source inputs is the most common water quality problem in the United States (USEPA, 1990, 1996). Nonpoint sources of P, however, can be either of natural or anthropogenic origin. Identifying correct sources of P is a very important process in urban stream management. In prior work, in the urbanizing Johnson Creek watershed, a subbasin of the Willamette watershed in Oregon, we found that stream water P was highly correlated with urban land uses whereas N concentrations were correlated with nonurban, rural land uses (Sonoda et al., 2001). Land use patterns alone, however, may not be sufficient to explain elevated levels of P in stream water. While land use may have significant effects on stream water quality, natural sources of P can have additional effects on receiving water. In a recent study, we found that beneath-stream shallow groundwater could be a source of P within nonurban areas of Johnson Creek watershed (Sonoda et al., 2002). In the present study we investigated potential natural sources of P to the stream including beneath-stream shallow groundwater and near-stream soil P content and other soil chemical parameters in both urban and nonurban areas of Johnson Creek watershed. Further, we investigated the relative significance of natural sources of P on surface water P concentrations and flux compared with surrounding land use patterns.

Natural availability of P in terrestrial ecosystems is limited by regional geochemistry; soil factors related to P input to streams include the amount of P available in the soil matrix, the amount of Al and Fe that can adsorb P, and the soil pH that determines release and retention of P. Nearly all P in terrestrial ecosystems originates from calcium phosphate minerals, especially apatite ($Ca_5(PO_4)_3OH$) (Schlesinger, 1997). As rock weathering progresses, it releases reactive (biologically available) P to the environment. Phosphorus adsorption to Al and Fe oxides, however, can occur to limit availability of P to the environment. Once P is occluded within Al or Fe hydrous oxides, it becomes unavailable to plants and microbes (Smeck, 1985). For example, Foppen and Griffioen (1995) reported the importance of the Fe(II)/PO_4 ratio and pH during groundwater seepage as P was stored as PO_4–bearing iron hydroxides.

In the case of saturated soils, such as in wetlands and in low gradient riparian areas, P adsorption rate to soil has been related to the amount of extractable Al in soil (Richardson, 1985). Furthermore, anaerobic soils release more phosphate to soil water than aerobic soils (Patrick and Khalid, 1974). For a given soil, P becomes more mobile under saturated conditions as the soil becomes more reducing with increasing anoxic conditions. Phosphorus adsorption in soil, in contrast, tends to increase as the soil dries, most likely due to increases in Al and Fe oxide concentrations as soil is exposed to air (Qiu and McComb, 2002). Since adsorption of P to Al and Fe oxides is favored under acidic conditions, P becomes more mobile under more neutral pH conditions. As a system, geological differences such as P weathering rates and P release from Al and Fe oxides, availability of mineral P, and P affinity of local soil can further complicate the natural background level of P input to the stream. Moreover, Evans et al. (2004) reported the importance of metal oxyhydroxide adsorption of P in bedload sediments and streams. For this study, it was particularly important for us to investigate P, Al and Fe contents in the soil matrix, and soil pH when quantifying natural sources of P to the stream as our study region, the Willamette River Valley, is naturally high in native P which is 10 times greater when compared with national average of 600 mg TP kg^{-1} (Abrams and Jarrell, 1995). Moreover, Abrams and

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Abbreviations: SRP, soluble reactive phosphorus; TP, total phosphorus.

Jarrell (1995) concluded that approximately 50% of soils in the nearby Tualatin River Basin were potential nonpoint P sources to both surface and subsurface waters. Mayer and Jarrell (1995) based analysis of seasonal variation on fraction of colloidal P and Fe, and suggested that dominant sources of P in Tualatin River Basin were most likely groundwater, especially during low flow season. During the wet season, however, the majority of P was in particulate P form suggesting surface runoff origin.

Recent studies in P sorption and desorption characteristics of the soils have suggested that desorption of P linearly increases after soil saturation with P reaches 10% (Heckrath et al., 1995; Hooda et al., 2000). Hence, if a soil is subjected to long-term P loading from P-rich groundwater or runoff, it can became saturated with P and lose the ability to adsorb P. Under such conditions, once P is released to groundwater, P-enriched groundwater can become a source of P to the stream. Many studies have shown that the exchange of water between the subsurface and a stream has a strong influence on stream chemistry (Pionke et al., 1988) and nutrient fluxes (Fiebig et al., 1990; Triska et al., 1993). In the Taupo volcanic zone in New Zealand, for example, naturally occurring spring water was found responsible for substantial P loading as high as 0.3 g P m^{-3} to some lakes (Timperley, 1983). Groundwater as a source of nutrients to streams has been reported in Colorado, Nebraska, Wyoming (McMahon et al., 1994), and western Australia (Taniguchi et al., 1997). These studies suggest possible relationships between high P concentrations in regional groundwater and P concentrations in receiving surface water bodies.

Our objective in this study was to understand relationships and significances of elevated stream P concentrations and both anthropogenic and natural sources of P within the urbanizing stream.

MATERIALS AND METHODS

Study Area

Land Use

We selected the Johnson Creek watershed, a 140-km^2 area in Portland, Oregon, as our study site. At 38 km in length, Johnson Creek is one of the largest remaining free-flowing urban streams in Oregon. Johnson Creek originates in an agriculturally based rural area and terminates in an urbanized area. Hence, Johnson Creek receives nutrients from both rural/agricultural and urbanizing areas. Due to extensive urbanization, almost all tributaries in the northwest side of the urban growth boundary of the Johnson Creek basin have been removed and replaced by a culvert and street drainage network (Fig. 1a). Approximately 38% of the tributaries within urbanized area were piped or relocated by development (Meross, 2000). Within the Portland region, which comprises most of the urbanized area of the watershed, approximately 23% of the precipitation drains to groundwater through storm water sumps, approximately 8% is directed to combined sewer system, and 6% is hydrologically disconnected from the creek (Meross, 2000). The remaining of approximately 63% of the water drains to Johnson Creek via overland flow or storm water drain pipes which directly discharge to the creek. These figures do not account for water loss due to evapotranspiration. As of March 2003, 29 storm water permits under the National Pollution Discharge Elimination System Permit Program were issued by the Oregon Department of Environmental Quality within the Johnson watershed, most of them within the urbanized areas. These permits allow facilities to discharge storm water and runoff directly to the stream via pipes—11 construction storm water permits, 13 industrial storm water permits, 3 combined animal feeding operation permits, 2 industrial hydrocarbon cleanup-related permits, and 1 domestic sewage drain field permit (Johnson Creek Watershed Council, 2002). These figures do not include permits pending or those that had expired at the time of the study. In addition to pipes, there are over 50 bridges that cross the main stem of Johnson Creek. Many of these bridges have roadside ditches and culverts that convey runoff directly to Johnson Creek. Because of a clearly defined urban growth boundary (Fig. 1a), the Johnson Creek watershed provides an opportunity to study effects of change in land use on stream water quality.

Underlying Geology

Within the Johnson Creek basin, there are two distinctive hydrogeologic units: the Troutdale Gravel (TG) aquifer and the Unconsolidated Sedimentary (US) aquifer that supply regional groundwater (Swanson et al., 1993) (Fig. 1b). The older formation, the TG formation, is a consolidated sandy gravel layer with lithic sandstone lenses and beds derived from Pleistocene volcaniclastic conglomerates. The TG formation is exposed to land surface and has a thickness range of 20 to 120 m, covering most of the east side of Johnson Creek basin. The remainder of the basin is composed of the US formation, a late Pleistocene catastrophic flood deposit and Quaternary alluvium, which is mostly comprised by flood plain deposits of the Columbia and Willamette rivers. The US formation lies on top of TG formation and has a thickness of about 30 m from the surface. It is important to note that most urban land use areas lie on top of the US aquifer, whereas most of nonurban land use areas overlap with the TG aquifer (Fig. 1a and 1b). Regional groundwater taken from these two hydrological units, however, did not vary in N and P concentrations (Sonoda et al., 2001).

Hydrology

Johnson Creek has an average gradient of 0.5%, with a steeper upper section (0.8% gradient) and 0.4% in middle section (McConnaha, 2003). Due to changes in land use, increases in impervious surfaces, modification on channel morphology, and other physical changes along the stream, Johnson Creek has become a relatively flashy stream over recent decades (Clark, 1999). Highest discharges normally occur during winter months (December, January, and February) in response to increased rainfall and higher amounts of surface runoff as soils become saturated. During dry summer months (July, August, and September), however, the stream receives a minimal amount of precipitation, and most stream water is fed by groundwater throughout the watershed (Johnson Creek Watershed Council, 2002). The USGS has three gauging station along the Johnson Creek: Milwaukie (river mile [RM] 0.7), Sycamore (RM 10.7), and Regner (RM 16.3). Strong relationships (typical linear regression R^2 values were 0.95 or higher) between stream flows measured at these gauging station and corresponding river miles indicate that stream discharge in Johnson Creek increases linearly from headwater to downstream throughout the year (Gloss, 2004). During the last 10 yr, monthly average flow varied from 3400 to 3700 L s^{-1}

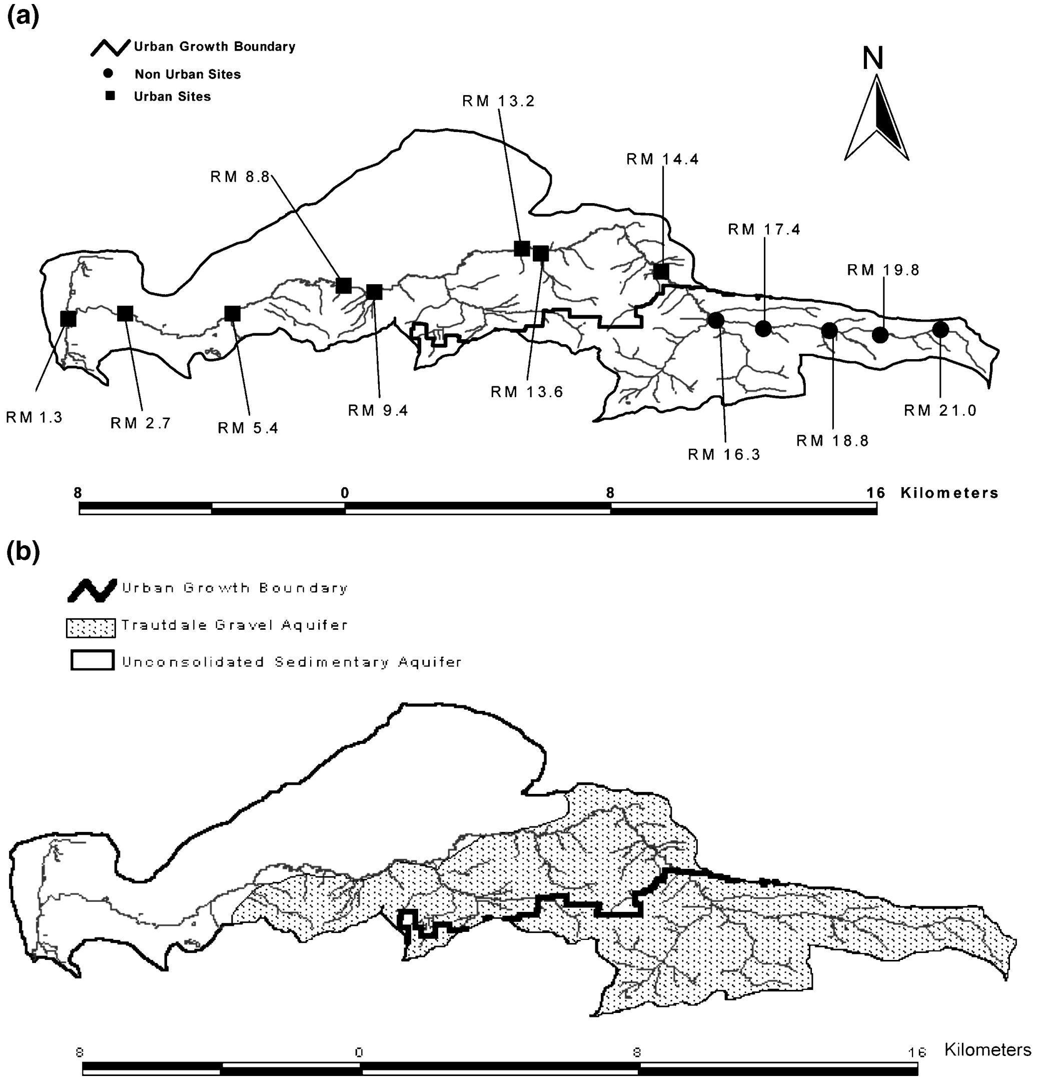

Fig. 1. (a) Map of the Johnson Creek watershed, Portland, OR, USA. Solid squares indicate sample sites within urban land use areas, while solid circles indicate sample sites in nonurban areas. (b) The shaded area indicates Troutdale Gravel aquifer (TG), while the nonshaded area indicates Unconsolidated Sedimentary aquifer (US) at surface level. The thick line indicates location of urban growth boundary (UGB); west of the UGB are urban land use areas, while east of the UGB are nonurban land use areas. RM = river miles from the mouth of the stream.

for winter months and less than 140 L s^{-1} during summer months at USGS Sycamore gauging station (RM 10.2). Bankfull discharge (19500 L s^{-1}) at Sycamore gauging station occurs about 3 times per year and flood stage (30600 L s^{-1}) occurs about 1.8 times per year (Johnson Creek Watershed Council, 2002). During most winter months riparian soils are near-saturated, whereas during summer months riparian soil moisture levels become very low.

Site Selection

Thirteen sample sites on the main stem of Johnson Creek were selected to collect monthly stream water and beneath-stream groundwater samples (Fig. 1a). The first 8 sites starting from RM 1.3 (above the confluence of Crystal Springs and Johnson Creek) to RM 14.4 were located within urban land use areas which is west of the urban growth boundary, while the last 5 sites from RM 16.3 to RM 21.0 were located within nonurban land use areas, which is east of the urban growth boundary. All soil samples were also collected from adjacent banks on both sides of the 13 sample sites.

Sampling

Monthly surface water and beneath-stream groundwater samples were taken on the second weekend of the month regardless of weather or flow condition from December 2000 to December 2001. Water samples included storm flow condition and base flow condition. Beneath-stream groundwater samples were collected using a mini-piezometer (Lee and Cherry, 1978) installed in the middle of the stream at 60 cm below the stream bed surface. All surface water samples were collected at the middle of the stream several meters downstream from mini-piezometer locations. To avoid contamination, all groundwater samples were collected in acid-washed 250 mL high density polyethylene (HDPE) Nalgene sample bottles after the conductivity and water temperature stabilized. All water samples were stored in an ice chest and transported to the laboratory at Portland State University for nutrient analysis. During May 2000, at each of the 13 sample points, soil sampling was conducted. At each sample point, two sites were randomly selected within 5m from the stream on each side of the stream bank. Soil samples were extracted using a hand auger. Samples were taken from both the A soil horizons (sample depths ranged from 5 to 50 cm, depending on A horizon depth) and B soil horizons (sample depths ranged from 50 to 80 cm, depending on B horizon depth) at each site, for a total of 108 soil samples.

Water Sample Analysis

For soluble reactive phosphorus (SRP), samples were filtered through Millipore type GF/F filters (0.45-μm pore size) using a Nalgene hand pump filtration within 6 h of collection. Concentrations of P were determined using the ascorbic acid method (Wetzel and Likens, 1991). Total phosphorus (TP) concentrations were determined using alkaline potassium persulfate digestion of nonfiltered samples (Ameel et al., 1993) followed by the ascorbic acid method. No replicate samples were collected at the field. However, blanks and standards were used for every analysis to ensure the quality of measurements. For all colorimetric tests, a Milton Roy Spectronic 401 (Milton Roy, Ivyland, PA) was used.

Soil Sample Analysis

The samples from each horizon were taken to the lab, air-dried, mixed thoroughly, and sieved to pass through a 2-mm mesh screen before analyses. The soil analyses included soil pH (McLean, 1982), water-soluble P (Olsen and Sommers, 1982), base (NH_4HCO_3)-soluble P (Olsen and Sommers, 1982), acid-soluble P (Bray P1: measure of P available for plants) (Bray and Kurtz, 1945), and total P by sodium hypobromite oxidation (Kuo, 1996). Phosphorus concentrations in all extracts were determined using the ascorbic acid method. In addition, soil samples were digested with aqua regia and hydrofluoric acid in a closed vessel (Hossner, 1996) to extract Al and Fe. Aluminum and Fe concentrations in the digested solutions were determined by atomic absorption spectroscopy.

Data Analysis

Annual average stream and beneath-stream groundwater nutrient concentrations from urban ($n = 8$) and nonurban ($n = 5$) sites were compared using *t* tests and Mann–Whitney rank sum tests. Using December 2000 through December 2001 samples, average stream water P concentrations from each sample site were compared with beneath-stream groundwater P concentrations for any correlations using Pearson product moment correlation and Spearman rank order correlation. Average P flux at each site was calculated by multiplying P concentration and estimated discharge value. We estimated discharge values by interpolating corresponding river miles at each site to linear regression obtained from three USGS gauging station readings and their river miles on the day of sampling. Regressions between river miles and gauging station readings showed strong relationships (i.e., $r^2 > 0.9$). All soil chemistry parameters (i.e., soil pH, acid-soluble P, base-soluble P, water-soluble P, total P, Al, and Fe) were averaged for each soil horizon (A and B) at each site. Average soil chemistry parameters from urban and nonurban sites were compared using *t* tests and Mann–Whitney rank sum tests. In addition, average beneath-stream shallow groundwater P concentrations from each sample site were tested for correlations among all soil chemistry parameters for each site, using a Pearson product moment correlation test. Further, any soil physical parameters that were found to have significant correlation with the beneath-stream shallow groundwater P concentrations were used as independent variables along with variables of near-stream land uses in a forward stepwise multiple regression analysis, with dependent variables of stream water P concentrations and flux. We used the ArcView GIS (Environmental System Research Institute, Redlands, CA) and a regional land information system (Metro Regional Services, Portland, Oregon), to quantify different land uses (Table 1) and their relative percentages within 30-m circular buffer zones that extended from the sample locations for all sample sites (Sonoda et al., 2001). The 30-m radius was found to be the most correlated with stream water nutrient concentrations in our previous study. For more detailed information about classification of land use, determination of buffer shape and size, and assumptions underlying land use as a physical parameter, please refer to Sonoda et al. (2001).

Average stream water P concentrations and P flux were calculated based on this study data: December 2000 through December 2001 ($n = 12$ mo) and the previous study data: March 1998 through December 1999 ($n = 22$). Average P concentrations and flux at each site were tested for correlations among area of different land uses within 30-m buffer zones of each sample site and soil chemical parameters using a Pearson product moment correlation analysis.

Regarding surface water P concentrations, we assumed uniform in-stream processes throughout the stream. Since Johnson Creek is a very flashy stream and discharge increases linearly, it was reasonable to assume that P intake or release by the periphyton community did not differ greatly from site to site. Before performing the regression analysis between land use and soil chemical parameters and P, all P concentration and flux were analyzed for possible relationships with a simple cumulative effect of the stream by performing a linear regression between the concentrations and river miles. This "detrending" corrected possible positive correlations between stream discharge, which is a function of river miles, and increase in nutrient concentrations that occurs often in streams (Kleiber and Erlebach, 1977; Langmuir, 1997). When the correlation between nutrient concentration and river miles was more than 50% of nutrient variation was explained by changes in river miles ($R^2 > 0.5$) the residual of the linear regression between nutrient concentrations and river miles (i.e., variance due to other than the simple cumulative effect of the stream) was used for the forward stepwise multiple regression analysis with land uses.

Table 1. Land use and soil chemistry parameters used in forward stepwise multiple regression analysis. All land use categories and descriptions are modified from the Regional Land Information Lite (RLIS) Data Dictionary prepared by Metro (Metro Regional Services, Portland, OR).

Land use category	Descriptions
Rural/agric.	rural and agricultural uses (activities suited to commercial-scale production, typically with lot sizes ≥12 150 m^3; residential uses permitted in rural sizes ≥4005 m^3)
SF Res	single family residential uses (detached housing with various lot sizes)
MF Res	multi-family residential uses (housing accommodating densities ranging from two [duplex] or more units)
Mixed use	includes mixed land use and commercial activities (e.g., combined residential and employment uses)
Industrial	industrial uses (districts permitting light industrial and more processing, heavy manufacturing, warehousing and light processing, and fabrication activities; may allow some commercial activities)
Park/open	typical parks, open spaces, and green spaces
Soil chemistry parameters	
Fe in A horizon	amount of Fe present in A horizon
Fe in B horizon	amount of Fe present in B horizon
Al in A horizon	amount of Al present in A horizon
Al in B horizon	amount of Al present in B horizon

RESULTS

Soil Chemistry

From the types of P measured in soil samples (i.e., water-soluble P, acid-soluble P, base-soluble P, and total P content from A and B soil horizon) we found significant differences in water-soluble and acid-soluble P content between urban and nonurban soils (Fig. 2). Both A and B soil horizons in the urban area had a significantly higher water-soluble P concentration (Fig. 2a). In contrast, acid-soluble P concentrations in both A and B soil horizons were higher in nonurban areas (Fig. 2b). There were no significant differences in base-soluble P or total P concentration levels (Fig. 2c and 2d). These results showed no consistency in P contents among soil samples taken from urban and nonurban areas, indicating total availability of P in the soil does not vary greatly among urban and nonurban land use areas of Johnson Creek watershed.

Soil pH was significantly higher in the urban area in both A and B soil horizons (Fig. 3a). We also found that both Al and Fe contents were significantly higher in nonurban areas compared with urban areas (Fig. 3b and 3c). Given that the acidic soil favors P adsorption to Al and Fe oxides, these results suggest the possibility of greater retention of P within nonurban areas by Al and Fe in soil. Beneath-stream groundwater SRP was negatively correlated with Al in B soil horizon and Fe in A soil horizon (Fig. 4a and 4c, Table 2). Beneath-stream groundwater TP was also negatively correlated with Al in B soil horizon and Fe in A soil horizon (Fig. 4b and 4d; Table 2). These results indicate that a presence of P adsorption to Al and Fe oxides may be related to the release of P to groundwater and stream water in the Johnson Creek watershed.

Stream Water and Beneath-Stream Ground Water Chemistry

Annual average stream water SRP and TP concentrations were significantly higher ($p < 0.001$ and $p = 0.031$, respectively) in urban land use areas (Fig. 5a and 5b). Similarly, annual average beneath-stream shallow groundwater SRP and TP concentrations were significantly higher ($p < 0.001$ and $p = 0.013$, respectively) in urban land use areas (Fig. 5c and 5d).

In further analysis of seasonal difference in wet and dry seasons using a *t* test and Mann–Whitney rank sum test, we found that in both dry and wet seasons there were significantly higher P concentrations in urban areas compared with nonurban areas (Table 3). The beneath-stream groundwater P concentrations, however, did not vary significantly between seasons (Table 3). Both SRP and TP flux were higher during wet season compared

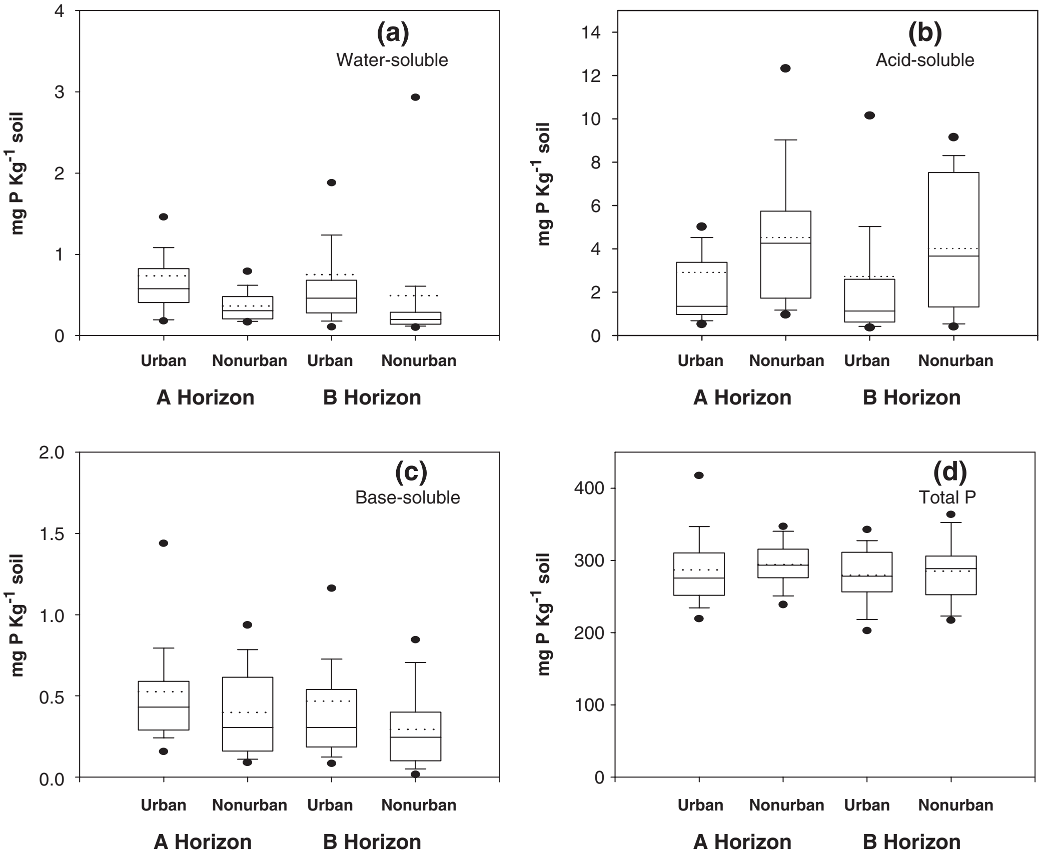

Fig. 2. Mean soil phosphorus content. Shown from urban ($n = 8$) and nonurban ($n = 5$) sites are: (a) mean water-soluble P content, (b) mean acid-soluble phosphorus content, (c) mean base-soluble P content, and (d) mean total P content. Dots indicate range of variation; whiskers indicate 5th and 95th percentiles; solid lines indicate median values; and dashed lines indicate means. Median values between urban and nonurban samples were significantly different in (a) water-soluble P contents and in (b) acid-soluble P contents for both the A and B horizons ($p < 0.05$).

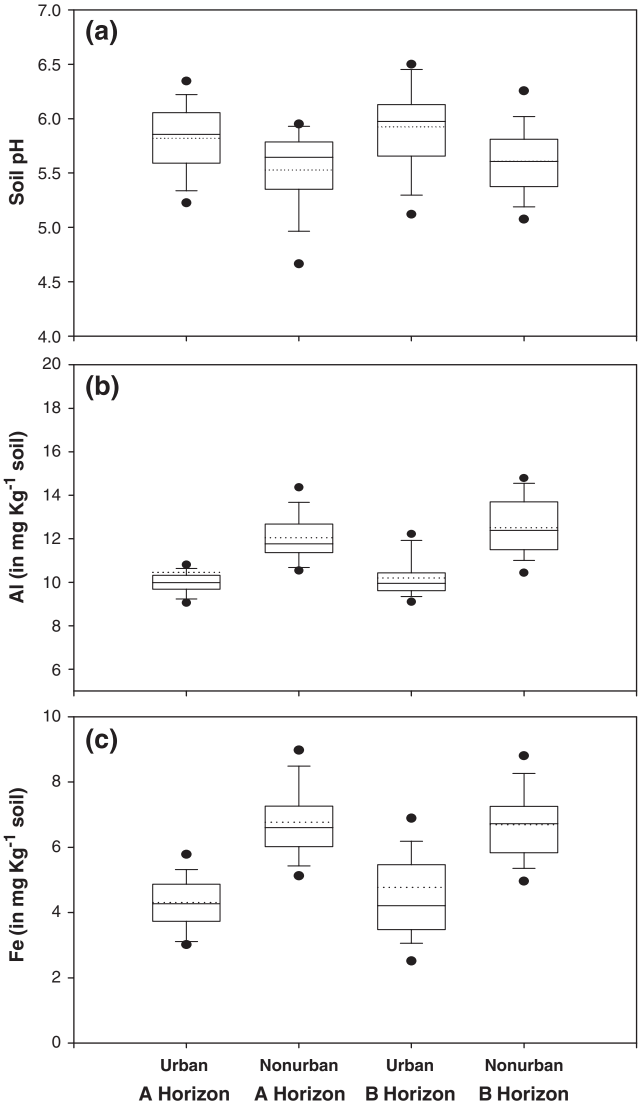

Fig. 3. Mean soil pH, soil aluminum content, and soil iron content. Shown from urban ($n = 8$) and nonurban ($n = 5$) sites are: (a) mean soil pH, (b) mean soil Al content, and (c) mean soil Fe content. Dots indicate range of variation; whiskers indicate 5th and 95th percentiles; solid lines indicate median values; and dashed lines indicate means. Means between urban and nonurban samples were significantly different for soil pH in the A and B horizons ($p < 0.01$). Median values between urban and nonurban samples were significantly different (t test) for soil Al and Fe in the A and B horizons ($p \leq 0.001$) (after Sonoda et al., 2002).

with dry season (Fig. 6a and 6b). Continuous SRP flux during dry season when there is little or no surface runoff in Johnson Creek watershed indicated groundwater as a significant source of SRP in Johnson Creek (Fig. 6a).

Both SRP and TP stream water and beneath-stream shallow groundwater samples from nonurban land use areas had strong regression coefficients (Fig. 7b and 7d), indicating beneath-stream shallow groundwater as a major source of P within nonurban land use areas. There were, however, no significant relationships between surface water and beneath-stream shallow groundwater P concentrations within urban land use areas, indicating the presence of other sources of P in the urban areas in addition to naturally occurring groundwater sources (Fig. 7a and 7c).

Stream water SRP concentrations and SRP and TP loadings all increased from headwater areas to the lowest sampling point on the stream (Fig. 5a, 6a, and 6b). Phosphorus loadings were strongly correlated with river miles ($R^2 = 0.79$ for stream water SRP, $R^2 = 0.96$ for SRP flux, and $R^2 = 0.87$ for TP loading). These trends were expected as both discharge and P concentrations increased from headwater toward the mouth of stream. Detrended stream water SRP concentration correlated positively with the industrial land use (Table 2). Detrended SRP flux correlated positively with multiple-family residential land use and park/open land use patterns. Soluble reactive P loading, however, negatively correlated with mixed land use. Detrended TP flux also negatively correlated with single family residential land use (Table 2). All near-stream groundwater P correlated negatively with soil chemistry indicating less P adsorption to Fe or Al (Table 2).

Land Use Pattern versus Soil Chemistry Factors for Stream Water Phosphorus

For the forward stepwise multiple regression analysis between stream water SRP concentrations, flux and soil chemistry, and land use parameters, we found that the near-stream land use patterns were more highly correlated than near-stream soil chemistry or groundwater P concentrations (Table 4). Stream water TP had contributions from both land use pattern and soil chemistry. Groundwater SRP showed no relationship with either land use pattern or soil chemistry parameters. Groundwater TP was only related to near-stream soil chemistry parameters (Table 4). Soluble reactive P flux was correlated with mixed land use and multiple-family residential land use, wheras TP flux correlated with single family residential land use (Table 4).

DISCUSSION

In our prior study (Sonoda et al., 2001), we did not find a significant variation in groundwater concentrations of P in measurements in eight domestic wells throughout the watershed. We wish to emphasize, however, that even though no significant *variation* was found, groundwater input is yet an important source of P to Johnson Creek, whether in nonurban or urban areas. In the present study, we used shallow groundwater measurements to account for P variation from groundwater. We acknowledge that shallow groundwater can be affected by surface factors and is an incomplete measure of the full complexity of groundwater fluxes and inputs to a stream; however, it is at least a first approximation to a groundwater signal. The present study showed that both beneath-stream shallow groundwater and stream water P concentrations were higher in urban areas compared with nonurban areas (Fig. 5). Further, relatively unchanging SRP concentrations in the beneath-stream groundwater over a year (Table 3) suggested continuous input of P to the stream via

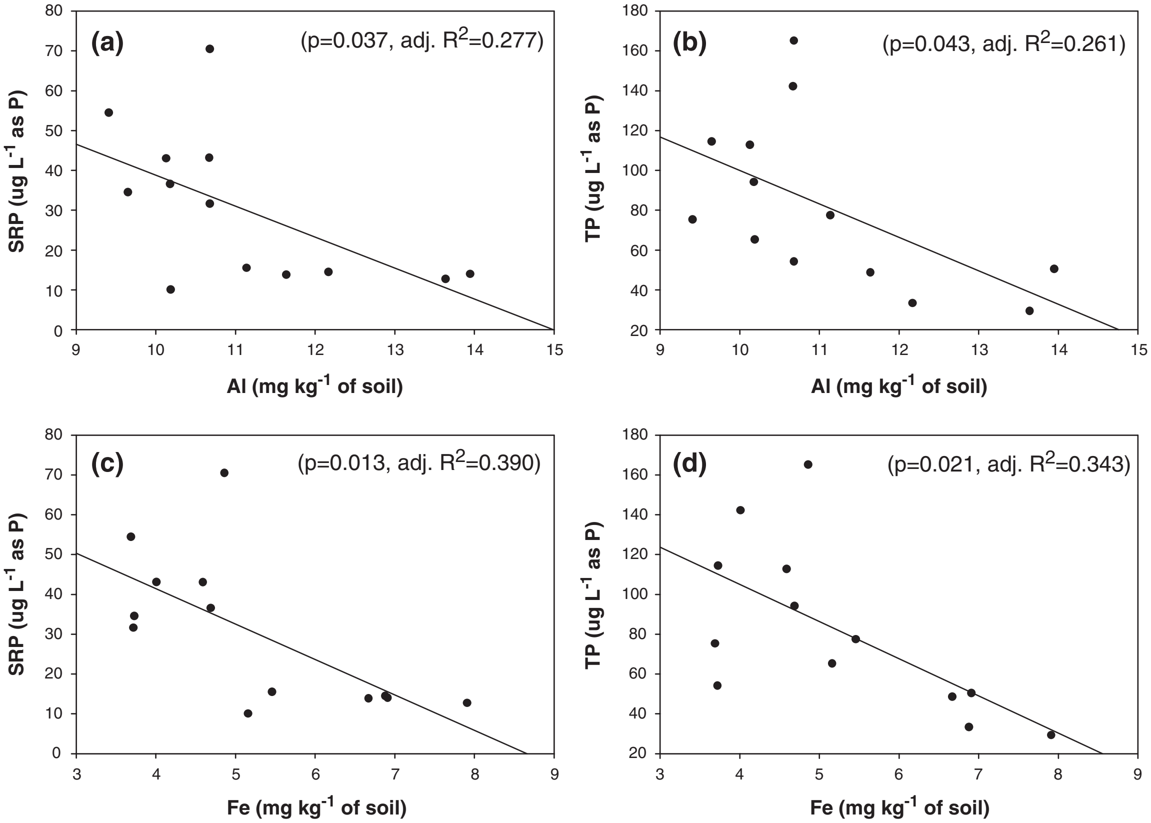

Fig. 4. Relationships between beneath-stream groundwater phosphorus concentrations vs. soil aluminum and soil iron contents at each site. Phosphorus concentration values are based on annual average ($n = 12$), whereas soil data are based on an average of 4 samples per site. Shown are (a) groundwater soluble reactive phosphorus (SRP) vs. Al in the B horizon, (b) groundwater total phosphorus (TP) vs. Al in the B horizon, (c) groundwater SRP vs. Fe in the A horizon, and (d) groundwater TP vs. Fe in the A horizon. Solid lines indicate significant ($p < 0.05$) linear regression slopes between near-stream groundwater phosphorus concentration and soil Al or soil Fe content.

groundwater regardless of season throughout the watershed. These results support findings by Mayer and Jarrell (1995). However, the relationship between stream water SRP and beneath-stream shallow groundwater SRP, which was very strong in nonurban areas, was masked by other factors in urban areas of Johnson Creek (Fig. 7a through 7d). The lack of significant relationships between stream water P and beneath-stream shallow groundwater P in urban areas (Fig. 7a and 7c) was likely due to possible input of surface runoff within the urban land use areas, in addition to the natural groundwater P inputs. It is likely that increases in paved surface area and storm drain density that can shunt P-rich runoff to the stream within urban areas were responsible for increases in additional P to the stream (Sonoda et al., 2001). Most P in the natural environment is likely to bind to soil particles or be taken up by biota within riparian areas. Effects of urbanization, however, may be limiting these natural processes of P sorption by soil and of biological uptake of P within riparian buffer zones.

Table 2. Relations between phosphorus concentrations and land use and soil chemistry parameters based on Pearson product moment correlation. Values are correlation coefficients; asterisk (*) indicates statistical significance at $P < 0.05$.

	Stream water			Beneath-stream groundwater		P Flux (detrended)	
Land use category	SRP†	SRP (detrended)	TP‡	SRP	TP	SRP	TP
Rural/agr	−0.836*	−0.376	−0.604*	−0.686*	−0.619*	−0.023	0.502
SF Res	0.439	0.462	0.132	0.488	0.427	−0.082	−0.639*
MF Res	0.346	−0.028	0.716*	0.067	0.235	0.578*	0.313
Mixed use	0.179	−0.411	−0.025	0.020	−0.198	−0.687*	0.171
Industrial	0.054	0.849*	0.239	0.201	0.223	0.116	−0.112
Park/open	0.479	−0.0564	0.603*	0.309	0.480	0.588*	0.588
Soil chemistry parameter							
Fe in A horizon	−0.908*	−0.197	−0.733*	−0.664*	−0.631*	0.094	0.094
Fe in B horizon	−0.654*	−0.108	−0.482	−0.191	−0.131	0.095	0.015
Al in A horizon	−0.268	−0.152	−0.551	−0.283	−0.645*	0.147	0.482
Al in B horizon	−0.826	−0.333	−0.754*	−0.581*	−0.567*	0.080	0.223

† SRP, soluble reactive phosphorus.
‡ TP, total phosphorus.

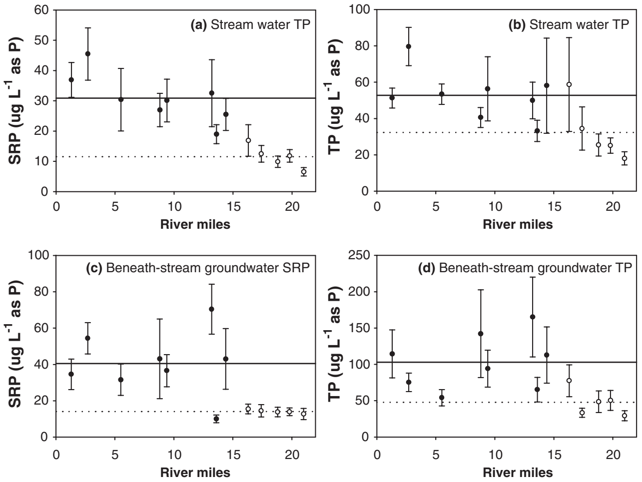

Fig. 5. Mean stream water and near-stream groundwater phosphorus concentrations ± 1 standard deviation. Phosphorus concentration values are based on annual average (December 2000 through December 2001; $n = 12$). Shown are: (a) mean stream water soluble reactive phosphorus (SRP), (b) mean stream water total phosphorus (TP), (c) mean beneath-stream groundwater SRP, and (d) mean beneath-stream groundwater TP. Solid circles indicate urban sites, whereas open circles indicate nonurban sites. Error bars are standard error from the mean. Solid horizontal lines indicate mean concentrations of all urban sites, whereas dotted horizontal lines indicate mean concentrations of all nonurban sites.

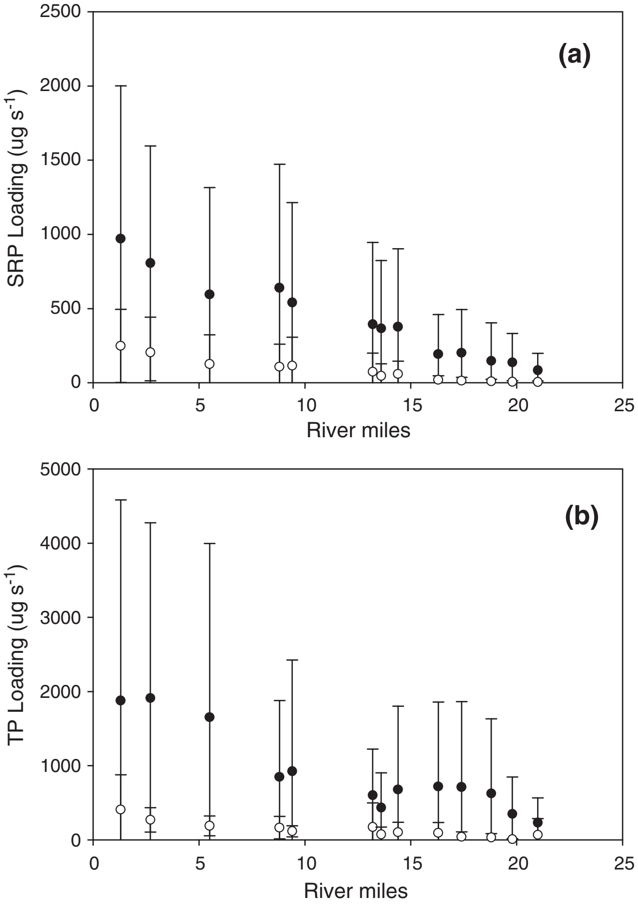

Fig. 6. Seasonal average phosphorus flux at each sample site. Closed circles indicate wet season average value ($n = 19$ for each location), whereas open circles indicate dry season average values ($n = 15$ for each location). (a) Soluble reactive phosphorus (SRP) flux in μg s^{-1}. (b) Total phosphorus (TP) flux in μg s^{-1}. Error bars are ± 1 standard error (SE) from the mean.

For riparian soils, we found soil samples taken from the nonurban area were significantly more acidic compared with soil samples from urban areas (Fig. 3a). Since low pH enhances P adsorption to Al and Fe oxides, if all other factors were equal, P retention by soil would be higher in nonurban areas. Significantly higher amounts of Al and Fe found in nonurban soils also suggested the possibility of greater P retention by soil within nonurban areas compared with urban areas. In the nearby Tualatin basin, Abrams and Jarrell (1995) suggested that lowland, nonandic soils, due to their high extractable P concentrations and lower P sorption affinity, could be a source for both surface and groundwater, and hence periodically saturated, or near-saturated soils could serve as sources of P to streams. Our statistical analysis found that both Al and Fe contents in soil were inversely correlated with beneath-stream shallow groundwater P concentrations (Fig. 4a through 4d). It is possible to speculate the process of P adsorption to Al and Fe oxides may be reducing the availability of P in the beneath-stream shallow groundwater within nonurban areas of Johnson Creek watershed. As seen in Fig. 4, however, more variability appeared in the relationship with P at lower concentrations of either Al or Fe, and we are not completely confident that the relationships in those figures are linear. More data points would need be collected to reduce those uncertainties. Given these concerns, it remains unclear whether Al and P soil geochemistry represents a major control on P contents in beneath-stream shallow groundwater.

Furthermore, we did not find any significant relationships between soil P content and beneath-stream shallow

Table 3. Summary of mean stream water and beneath-stream groundwater P concentrations ± 1 standard deviation. Wet season refers to October through April, whereas dry season refers to May through September. Asterisk (*) indicates significant differences between urban and nonurban sites at ($p < 0.05$).

	Stream water		Beneath-stream groundwater	
Parameter	Urban	Nonurban	Urban	Nonurban
	μg L^{-1}			
SRP† (wet season)	27.0 ± 5.3*	11.4 ± 1.6*	39.2 ± 26.0	12.4 ± 2.4
TP‡ (wet season)	49.6 ± 10.3*	28.5 ± 8.0*	118.5 ± 58.8	58.5 ± 18.6
SRP (dry season)	39.7 ± 10.0*	11.8 ± 3.6*	40.4 ± 20.1*	15.0 ± 3.1*
TP (dry season)	76.5 ± 16.8	44.0 ± 14.6	84.9 ± 20.3*	39.5 ± 21.3*

† SRP, soluble reactive phosphorus.
‡ TP, total phosphorus.

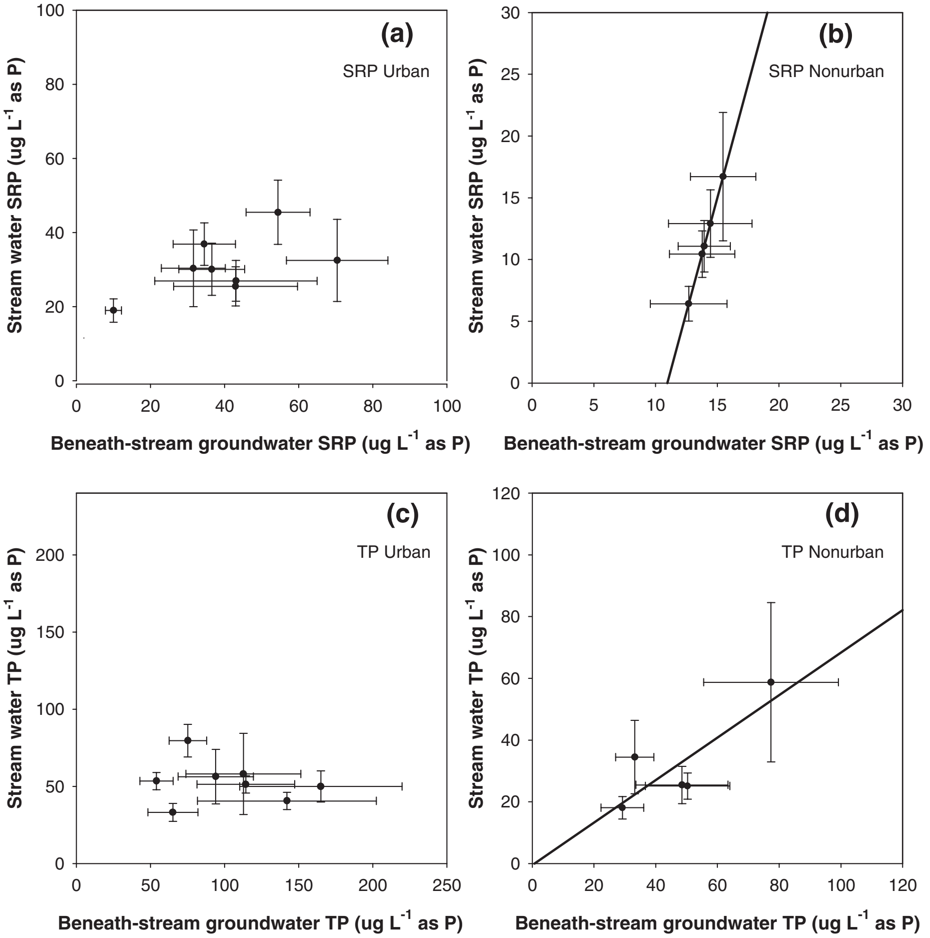

Fig. 7. Mean stream vs. near-stream groundwater phosphorus concentrations. Phosphorus concentration values are based on annual average (December 2000 through December 2001; $n = 12$). Shown are: (a) urban soluble reactive phosphorus (SRP), (b) nonurban SRP, (c) urban total phosphorus (TP), and (d) nonurban TP. Error bars are ± 1 standard error (SE) from the mean. Solid lines indicate significant linear regression slopes (for 7b, adj. $R^2 = 0.975$; for 7d, adj. $R^2 = 0.573$) between stream water and near-stream groundwater phosphorus concentrations (after Sonoda et al., 2002).

groundwater P concentrations. Lack of any significant relationships between soil P content and beneath-stream shallow groundwater P concentrations suggest that the amount of P released into beneath-stream shallow groundwater is not determined by the amount of P present in soil, but rather it is more related to P saturation levels. Hooda et al. (2000) reported that the amount of P that can be potentially released to water from soil is most likely related to the P saturation level of a given soil rather than P content or P sorption capacity. Our results support their findings.

These results for soil chemistry parameters and beneath-stream shallow groundwater P suggest that stream water P concentrations could be related to natural hydrogeochemical processes at least in the nonurban areas of Johnson Creek watershed. Based on our analyses, beneath-stream shallow groundwater TP concentrations were significantly correlated with Al and Fe contents in riparian soil, suggesting P adsorption to Al and Fe oxides throughout the system (Table 2). For stream water TP, in fact, we found a mixed result with both land use and soil chemistry playing a role in determining TP concen-

Table 4. A summary of forward stepwise multiple regression analysis. For descriptions of parameters, refer to Table 1.

	Most significant parameter		Second significant parameter		Third significant parameter		
		p-value		*p*-value		*p*-value	Adj. R^2
Stream water SRP (detrended)†	**Industrial**	**<0.001**	**SF Res.**	**0.002**	**Mixed use**	**0.007**	**0.931**
Stream water TP‡	**Al in B hor.**	**0.011**	**MF Res.**	**<0.001**	**GW TP**	**0.011**	**0.892**
Groundwater SRP	**Rural/agr**	**0.010**	–	–	–	–	**0.422**
Groundwater TP	**Al in A hor.**	**0.017**	–	–	–	–	**0.416**
SRP loading (detrended)	**Mixed use**	**0.003**	**MF Res.**	**0.009**	–	–	**0.739**
TP loading (detrended)	**SF Res.**	**0.019**	–	–	–	–	**0.409**

† SRP, soluble reactive phosphorus.
‡ TP, total phosphorus.

trations in the stream (Table 4). For stream water SRP concentrations, however, soil chemistry parameters, compared with the immediate surrounding land use pattern, had very little or no significant relationship (Table 4). When P flux were used, only land use parameters had significant regression coefficients. These statistical analyses indicated that land use might have some additional effects on stream water P concentrations and flux in this urbanizing watershed. Mechanisms of P loading processes caused by urbanization, however, requires further research.

It is probable that a decrease in riparian vegetation within urban land use areas (McConnaha, 2003) was an additional factor in SRP enrichment in stream water in Johnson Creek. The importance of riparian buffer areas for storage and retention of nutrients is well known (Yeakley et al., 2003) and near-stream soil areas have been found to alternate between sources and sinks of soil nutrients including P (Mulholland, 1992); however, identifying the sources of such P within the urban areas requires further study.

Another important difference between urban and nonurban land use areas of Johnson Creek watershed is the presence of storm drains. There are at least 29 storm water permits issued by the Oregon DEQ within Johnson watershed (most of them within the urbanized areas) which allows facilities to discharge storm water and runoff directly to the stream via pipes (Johnson Creek Watershed Council, 2002). When street runoff is directed to storm drains in urban areas, it bypasses the soil matrix and riparian vegetation, hence minimizing P retention by the near-stream environment.

Lower Al and Fe content in riparian soil in urban areas also suggested the possibility of less P sorption in urban riparian areas. Lack of clear relationships between beneath-stream shallow groundwater P and stream water P concentrations within urban areas (Fig. 7a and 7c), and rather weak relationships between Al and Fe and beneath-stream shallow groundwater P (Fig. 4) indicated, however, that hydrogeochemical processes alone were not sufficient to explain the elevated levels of P in stream water within urbanizing areas of Johnson Creek. The most plausible explanation for increase in P within the urban areas of Johnson Creek was that urbanization factors were a likely cause of increase in P input, in addition to the natural sources of P. Our study showed that, in addition to natural groundwater sources of P, both near-stream hydrogeochemical processes and urbanized land uses were related to P release to the stream in the Johnson Creek watershed.

CONCLUSIONS

We found continuous input of P to the stream water via beneath-stream shallow groundwater throughout Johnson Creek watershed. Beneath-stream groundwater P concentrations were significantly higher in urban areas compared with nonurban areas. Johnson Creek receives naturally high P groundwater especially within the urban areas. However, relationships between the stream water P and the beneath-stream shallow groundwater were only observed in nonurban areas. Lack of clear relationships between stream water and beneath-stream groundwater P within the urban areas was most likely caused by additional P inputs due to urbanization. Riparian soil analysis indicated P adsorption to Al and Fe oxides occurs throughout the watershed. Phosphorus released to the beneath-stream shallow groundwater is most likely controlled by P saturation levels rather than total P in soil. Set within the context of land use patterns, riparian soil chemistry helped explain some of the variance in stream water P concentrations. We conclude that both urban land use patterns as well as near-stream soil and groundwater chemistry were important in explaining stream water P concentrations in this urbanizing stream.

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