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Review of Storm-Event Water Quality Data

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Review of Storm-Event Water Quality Data

City of Bellevue

by
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Abstract

This report provides an analysis of stormwater quality based on data originally published in a city of Bellevue (Washington) authored report titled: *Characterization and Source Control of Urban Storm Water Quality, Volume 1 – Technical Report.* March, 1995. It examines the relationship between the level of impervious surface and receiving water quality present during storm events for several Bellevue catchments, and serves as a supplement to another larger Washington State Department of Ecology study titled: *Land Use, Impervious Surface and Water Quality in Redmond, Washington.*

While the city of Redmond has water quality data for many of its surface waters at base flow, it is short on its understanding of water quality under storm-event conditions. This situation is common for many communities, due to the difficulties in obtaining representative storm-event water samples. Fortunately, this is not the case for the city of Bellevue, because the city has been a focus of study concerning stormwater runoff, on a national and local level, for a number of years. The city of Bellevue is adjacent to Redmond, so the two municipalities share similar physical characteristics that affect natural surface water runoff processes. Also, both cities have highly modified these processes through urbanization and its associated increase in impervious surface levels.

The principal findings of the analysis include:

- The median storm-event concentrations and annual yields of a variety of pollutants, observed in receiving waters, were positively correlated to average catchment impervious surface levels. Driving this process is the positive relationship between average catchment impervious surface levels and corresponding storm event runoff yields (m^3/ha-storm event). Higher levels of impervious surface result in greater levels of surface water runoff, which in turn increase the transport of pollutants to receiving waters.

- Two general relationships were found between water quality parameter concentrations and impervious surface levels: one characterized as a supply limitation and the other a flow or transport limitation.

  (1) A pollutant supply limitation was indicated where increased impervious surface levels and, therefore stormwater runoff, resulted in lower parameter concentrations observed in receiving waters. This is primarily the result of dilution. This scenario applied to the water quality parameters pH, conductivity, and nitrate. For these parameters, the relative contribution of groundwater discharge comprising stream flow is the primary determinant on receiving water concentrations.

  (2) The most common relationship observed between pollutant concentrations and impervious surface levels is the situation when there is a sufficient reservoir of pollutant available on the land surface that receiving water concentrations are only limited by stormwater transport capacity. In this situation, the pollutant supply exceeds the transport

capacity. The greater the ability of excess runoff to mobilize the pollutant, as defined by increased runoff yield, the higher the receiving water concentrations observed. So, while at greater impervious surface levels there is a greater volume of runoff, there is also greater receiving water pollutant concentrations, and therefore loading, offsetting the potential effect of dilution. For this reason, in terms of receiving water pollutant concentrations, this is described as a flow limitation scenario. It applies to the majority of pollutants examined in this analysis including turbidity, total suspended solids, chemical oxygen demand, total phosphorus, ammonia, chemical oxygen demand, as well as the metals zinc and copper.

The findings of this work are not unusual. However, a benefit of this analysis is that it provides an alternative method to quickly assess the relative magnitude of storm-event flow and the concentrations of a variety of commonly collected pollutant indicators, based on varying impervious surface levels. These relationships can be applied within western Washington to better understand the water quality impacts associated with impervious surface generation and, hopefully, lead to alternative design approaches to minimize its generation.

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Background

This analysis of stormwater quality is based on data originally published in a city of Bellevue authored report titled: *Characterization and Source Control of Urban Storm Water Quality, Volume 1 – Technical Report. March 1995*. This analysis also serves as a supplement to another larger Washington State Department of Ecology study titled: *Land Use, Impervious Surface and Water Quality in Redmond, Washington.*

The city of Redmond, while having a baseline of water quality data for many of its surface waters at base-flow conditions, is short on its understanding of water quality under storm-event conditions. This is a common situation for many communities; due to the difficulties in obtaining representative storm-event water samples. Data contained in the Bellevue report are particularly useful because the sampling specifically targeted storm events. The city of Bellevue is adjacent to Redmond, so the two municipalities share similar physical characteristics that affect natural surface water runoff processes. Also, both cities have highly modified these processes through urbanization and its associated increase in impervious surface levels. Therefore, this analysis will leverage the Bellevue storm-event data as a means to provide further insight into the probable changes in Redmond's surface water quality due to stormwater runoff.

Study overview

Storm-event and base-flow water quality data were collected at nine monitoring stations on the major surface waters draining the city of Bellevue (Figure 1). The study also included three outfall stations that received runoff solely during storm events. Monitoring occurred between 1988 and 1993, and targeted storm events with associated precipitation levels of 2.5 millimeters (mm) or greater over a 24-hour period. Water quality parameters measured included flow; pH; conductivity; hardness; turbidity; total suspended solids; chemical oxygen demand; total phosphorus; ortho-phosphate; fecal coliform; oil and grease; total petroleum hydrocarbons; nitrate; nitrite; and ammonia. In addition, the metals lead, cadmium, zinc, nickel, chromium, and copper were measured.

Each monitoring event occurred over a six-hour period with the ultimate samples comprised of flow-weighted composites. Because the full storm event was not typically sampled, the results were reported as *sample* mean concentrations as opposed to *event* mean concentrations. As a reference, the length of the average storm event in the Bellevue area is about 11 hours (Ebbert, 1985). For additional information regarding the original data, the analytical methods used, and quality assurance and control information, refer to the referenced report. A table of the median values used in this analysis, by monitoring station, for both storm-event and base-flow conditions, is included in Appendix A.

Figure 1. Bellevue storm water monitoring stations and delineated catchments.

Study catchments

A total of 12 monitoring locations were included in Bellevue's study. However, this analysis includes only the monitoring locations that had perennially flowing water. Consistent with the city of Redmond analysis, the focus here is on the effects to receiving water quality from stormwater runoff.

Table 1 presents the representation of various land use types (as decimal) present within each of the monitored catchments. The level of impervious surface associated with each of the land uses, by catchment, is included in Table 2. This information provides a generalized determination of typical levels of impervious surface associated with specific land use types. The overall median impervious surface level for each land use is that observed for the data set. Figure 2 provides the average impervious surface level observed above each monitoring location (based on 2001 land use data).

Figures 3 and 4 contain information on measures of elevation and drainage area within the monitored catchments. Median values for average elevation and drainage area are 92 meters and 267 hectares, respectively. Among the stations, Coal and Mercer are the outliers, based on these measures. Mercer and Coal Creek have drainage areas that are approximately 12 and 6 times greater than the overall median. Also, both of these catchments have a substantially higher relief than the other stations and, therefore, have greater precipitation levels. This is particularly applicable to Coal Creek, which has a significantly greater proportion of its catchment at higher elevations than the other stations. As it will be discussed, for Coal Creek these physical characteristics have important consequences to its water quality.

Table 1. Area representation (as decimal) of various land use types within monitored catchments.

Stations	Single Family	Multi-Family	Insti/ Govern.	Office	Commercial	Industrial	Park/ Open	Freeway	Streets
W. Kelsey u	0.24		0.01	0.10	0.05	0.28	0.11	0.05	0.17
W. Kelsey d	0.36	0.03	0.02	0.08	0.03	0.13	0.20	0.03	0.12
Mercer	0.37	0.10	0.08	0.05	0.04	0.04	0.19		0.13
Coal	0.27	0.01	0.02			0.02	0.59		0.09
Meydenbauer	0.32	0.10	0.08	0.07	0.17	0.01	0.06		0.19
Sturtevant u	0.06	0.03	0.03	0.24	0.17	0.17	0.08	0.07	0.15
Sturtevant d	0.08	0.02	0.04	0.24	0.17	0.20	0.10	0.08	0.06
Wilkins	0.51	0.06	0.03	0.04	0.05	0.02	0.10		0.19
Phantom	0.44		0.04	0.03	0.03	0.16	0.17		0.12

Table 2. Representation of impervious surface levels (as decimal) observed for various land uses present within monitored drainages.

Stations	Single Family	Multi-Family	Institutional / Government	Office	Commercial	Industrial	Special Industrial	Park/Open	Freeway	Streets
W. Kelsey u	0.17	0.50	0.50	0.83	0.85	0.70	0.75	0.08	0.69	0.48
W. Kelsey d	0.20	0.61	0.26	0.81	0.85	0.72	0.75	0.03	0.68	0.51
Mercer	0.14	0.33	0.24	0.39	0.49	0.49		0.26		0.53
Coal	0.20	0.50	0.50			0.50		0.02		0.78
Meydenbauer	0.27	0.68	0.35	0.87	0.88	0.89		0.18		0.48
Sturtevant u	0.30	0.75	1.00	0.83	0.86	0.88		0.26	0.69	0.48
Sturtevant d	0.30	0.69	0.92	0.81	0.85	0.89		0.31	0.70	0.48
Wilkins	0.23	0.60	0.57	0.70	0.75	0.60		0.17		0.41
Phantom	0.22		0.63	0.47	0.47	0.65		0.94		0.47
Overall Median	**0.22**	**0.61**	**0.50**	**0.81**	**0.85**	**0.70**	**0.75**	**0.18**	**0.69**	**0.48**

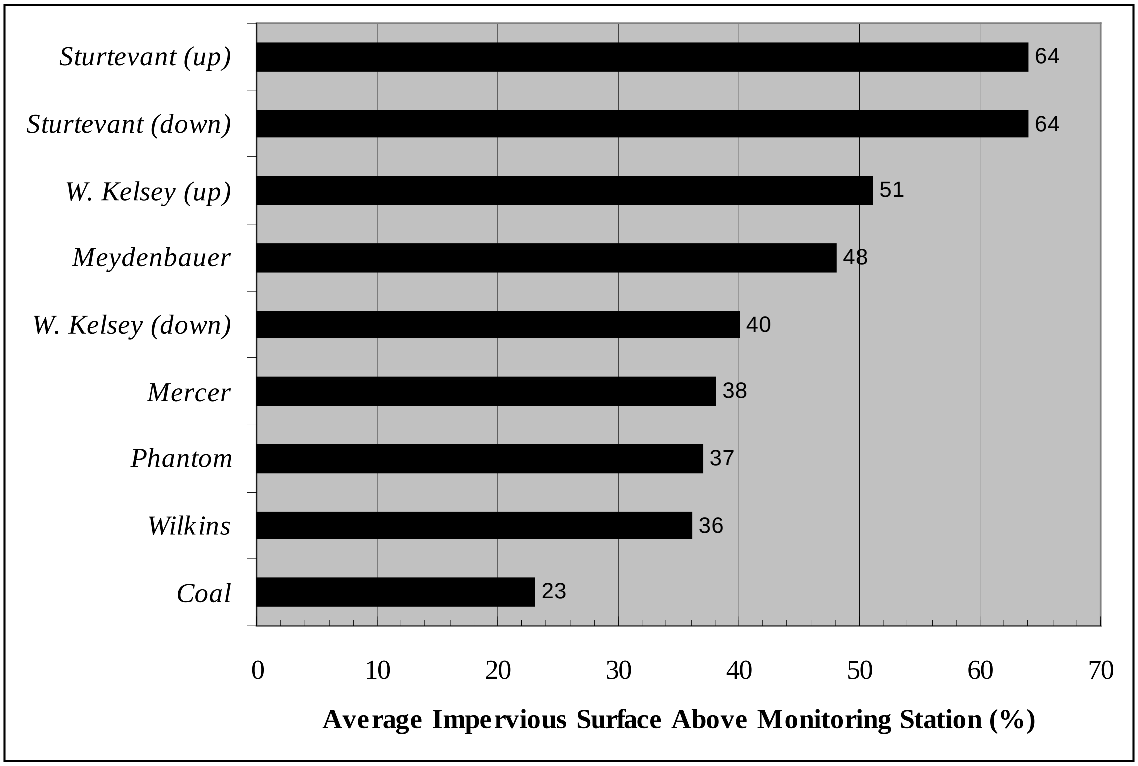

Figure 2. The average total impervious surface level (%) above each monitoring location.

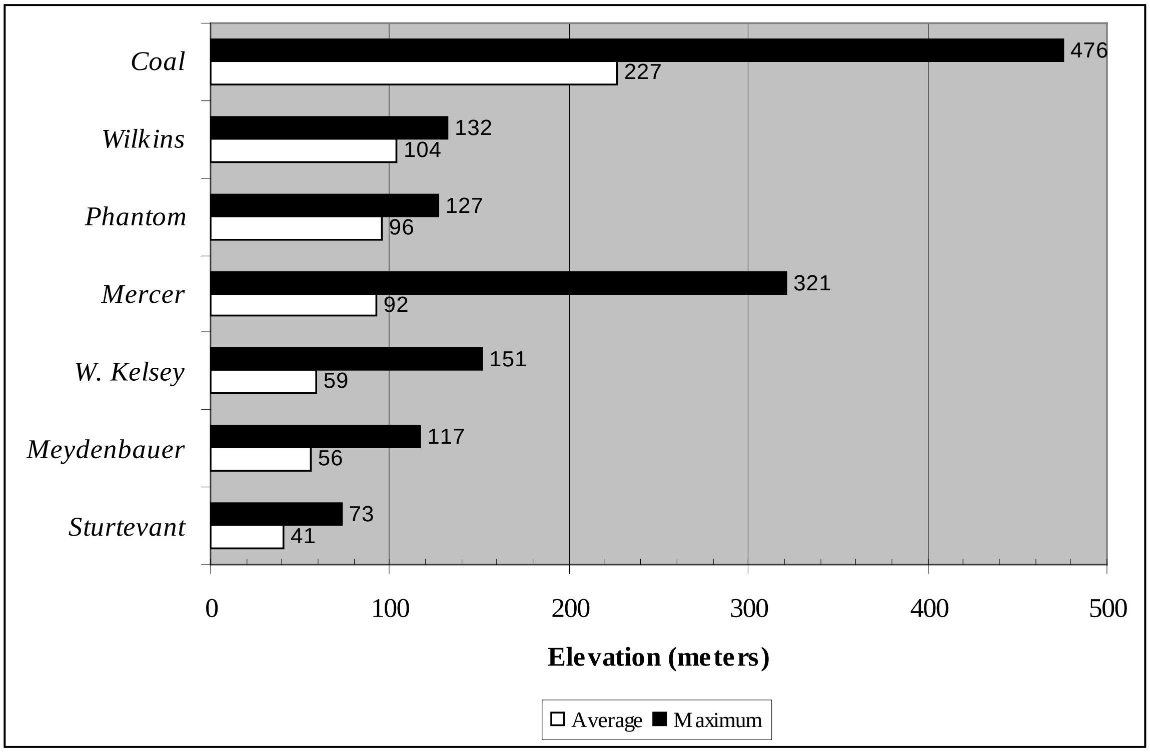

Figure 3. Average and maximum elevations (meters) within monitored catchments.

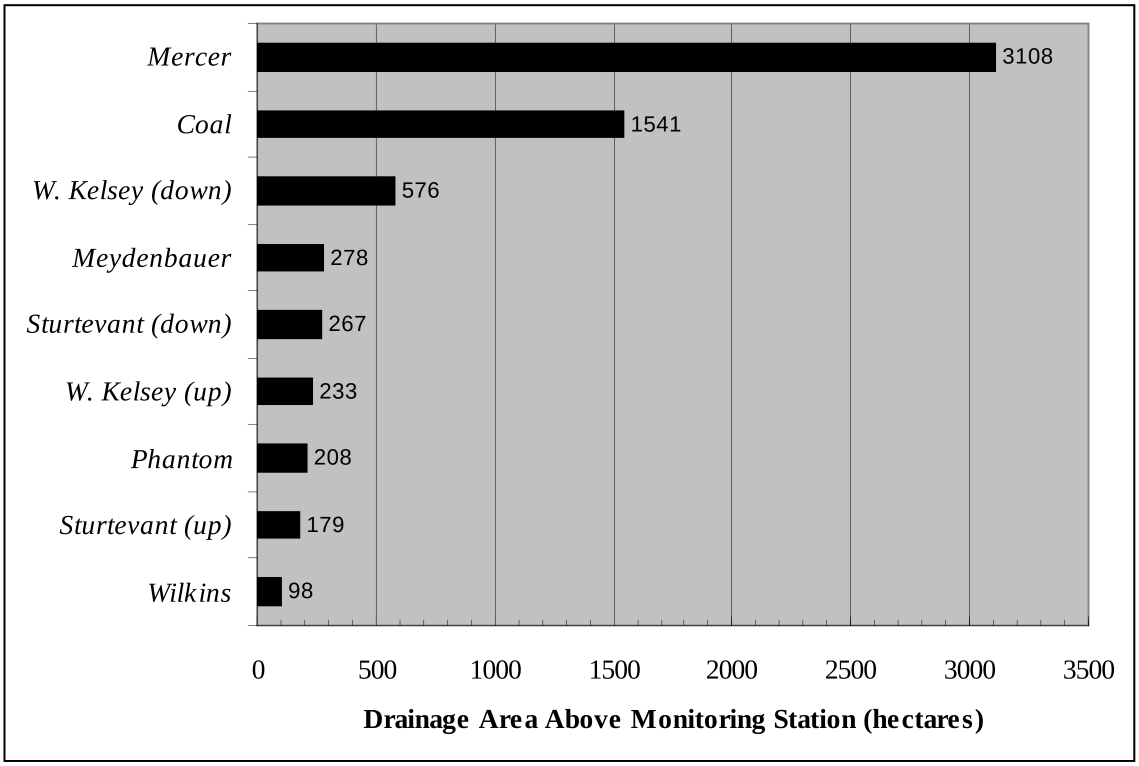

Figure 4. Drainage area (hectares) above monitoring stations.

Sampling conditions

Figure 5 presents box plots of daily precipitation levels, occurring on monitoring days, by station. The data were recorded at the Seattle-Tacoma Airport. Box plots present a percentile breakdown of data for comparative purposes. The top and bottom of the central box represent the 75th and 25th percentiles; the circle within the box represents the 50th percentile, or median; and the smaller squares extending from the top and bottom of the central rectangle represent the 90th and 10th percentiles, respectively.

Storm events, characterized by daily precipitation levels of 2.5 millimeters (mm) or greater, were targeted for monitoring. While it is recognized that precipitation levels observed in Bellevue may differ from those at the Seattle-Tacoma Airport (due to its proximity to the Cascade foothills), the presentation here is for comparative purposes to determine whether the storm events sampled were unusual or more representative of average conditions. In addition, the Seattle-Tacoma Airport weather station has an extensive record of rainfall, increasing its usefulness as a reference location. For this comparison, the long-term record of precipitation (1948-2006) and that observed during the monitoring period are presented. Consistent with the sampling criteria, the Seattle-Tacoma data excludes events less than 2.54 mm. As observed in Figure 5, in several cases the 10th percentile rainfall level extends below the 2.54 mm sample event criteria for the monitoring locations, potentially reflecting spacial and orographic differences between Bellevue and the Seattle-Tacoma Airport.

Considering the Seattle-Tacoma data, measurable rainfall occurs about 155 days per year at a median level of 3.6 mm. Approximately 40% of the time, recorded measurable precipitation levels are less than 2.54 mm. Rainfall levels at or above 2.54 mm occurs about 94 days per year, with a median level of 6.9 mm and an average of 10 mm. Of the average annual total rainfall observed at Seattle-Tacoma (973 mm), about 93% occurs during rainfall events at or above 2.54 mm.

With the exceptions of Wilkins and Phantom, the overall median storm-event precipitation level among the stations was 6 mm, slightly less, though close to the long-term median observed at the Seattle-Tacoma Airport. Levels ranged from 7.4 mm for Coal Creek to 3.6 mm for Sturtevant (d). Median precipitation levels sampled at Wilkins and Phantom were greater than those sampled for the other stations. The median precipitation level for both stations was about 12 mm, almost two times the median under which sampling occurred at the other stations.

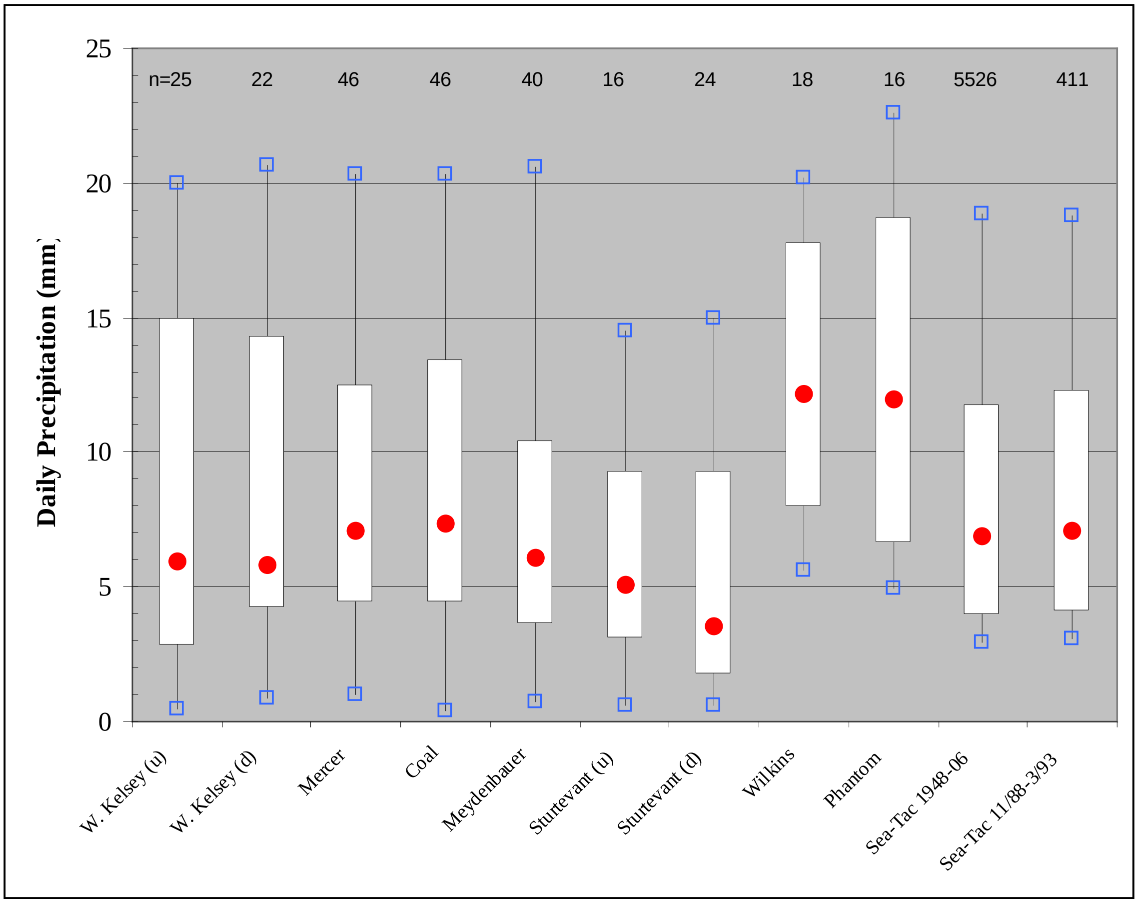

Figure 5. Box plots of daily precipitation totals (mm) observed on days monitoring occurred along with the longer term record observed at the Seattle-Tacoma Airport (1948-2006) and during the study period (1988-1993).

Analysis methods

The analysis methods used here are a departure from those presented in the original Bellevue report. This is primarily to stay consistent with the prior Redmond analyses. Towards that end, the water quality data were examined in terms of how the varying levels of impervious surface, present within the monitored catchments, affect stormwater generation and, in turn, the water quality of receiving waters. Because of the original study emphasis, there is more data available for storm-event monitoring in comparison to base-flow monitoring. For this reason, there is also a greater emphasis on using the storm-event data in this analysis. However, the base-flow data are also presented for comparative purposes.

For each station, overall median values were determined for each of the water quality parameters examined by monitoring type (base flow or storm event). Medians were only determined for the various analyses if the sample number was greater than four and the analyses reported as non-detected did not exceed 30% of the total sample number. This criteria limited analysis of the oil and grease, total petroleum hydrocarbons, lead, cadmium, nickel, and chromium parameters.

Central to this analysis is the presentation of a series of scatter plot figures, in which parameter median concentrations are plotted against the average impervious surface levels observed within the monitored catchments (refer to Figure 2 for average impervious surface levels). In addition, annual storm-event yields (mass per area per year) were calculated for many of the parameters. The yields were calculated by multiplying the median storm volume sampled, normalized by catchment area, by the median parameter concentration. This provided a pollutant yield per storm. To calculate annual yields, the storm-event yields were multiplied by 94, which is the average number of days per year precipitation equals or exceeds 2.54 mm. It is assumed that this precipitation level was the minimum required to initiate surface water runoff. Finally, the storm-event yield was multiplied by a factor of 1.6 to account for the fact that the study sample period of 6 hours encompassed only a portion of the typical storm event length.

Previous analysis of storm events (=>2.54 mm / 24-hours) within Bellevue found an average storm-event length of about 11 hours (Ebbert, 1985). At the Seattle-Tacoma airport, mean storm-event characteristics of rainfall intensity (0.79 mm/hr) and total precipitation (10 mm) indicate a length of about 13 hours (Perrich, 1992). These average storm lengths served as a guide, although the ultimate length of about 10 hours was chosen because it provided the best fit between the yields calculated through this approach and those reported previously by the Bellevue study. While the Bellevue study also calculated annual yields, that analysis did not extend to all the stations and parameters. Although different methods were used for stations and parameters in common between this analysis and the original Bellevue work, the estimated annual yields were similar (refer to Appendix B). (Yields were not calculated for the Wilkins station because no discharge measurements were collected there.)

These data are plotted against their associated average catchment impervious surface level. An underlying assumption in this analysis is that sufficient variability in storm events were sampled for each station (as they do not all share a common sampling date) and among the stations, so that the median storm volumes and parameter concentrations are representative and comparable.

The majority of the scatter-plots presented in this discussion were generated using the statistical software, Systat (V. 10). Within the scatter-plots, a line of fit between parameter concentrations and associated impervious surface levels was generated through the application of a locally weighted scatter-plot smoothing (LOWESS) method. LOWESS produces a smooth, or line of fit, by running along the x values (impervious surface) and finding predicted values from a weighted average of nearby y values (parameter concentrations and yields). A tension factor (f) of 1 was used in the plots. The tension factor gives the proportion of points in the plot which influence the smooth at each value. The intent of the plots, particularly provided the low sample number, is to present a general description of the various measures of water quality as they relate to impervious surface level, as opposed to their being used in a predictive capacity.

Average impervious surface levels were determined for the catchment area above each monitoring location using ArcGIS (V. 9.0) and its extension, Spatial Analyst. A grid of total impervious surface, based on 2001 land use, was used (Sanborn, 2005). The grid was based on a 30-meter resolution.

In addition, a combination box-scatter plot was generated for water quality parameter concentrations from the storm-event data. The box plot presents the variability in parameter observations, while the scatter component provides a relative separation of the monitoring data based on average catchment impervious surface levels. These figures, included in Appendix C, supplement the figures of median parameter levels included in the main portion of this report by providing an assessment of overall storm-event concentration variability.

Most of the figures do not contain labels associated with specific data points. The intent of this analysis is not to solely focus on the Bellevue catchments in particular, rather it is to examine how increased runoff, the result of increased impervious surface levels, affects receiving water pollutant concentrations and yields.

Discussion

Surface water runoff

While this analysis focuses on the relationship between impervious surface levels and various measures of water quality, the primary factor in mobilizing pollutants and delivering them to receiving waters is surface water runoff. For the majority of the catchments, as impervious surface levels increase there is a corresponding increase in the amount of surface runoff per area during storm events (Figure 6).

Within Figure 6, median storm-event volumes are normalized by catchment area. Normalizing, or dividing the median runoff volume by catchment area, places each of the sites on an “equal footing” for comparative purposes. (The storm-event runoff yields depicted in Figure 6 also include base flow.)

Among the stations, there is a strong positive relationship between the level of impervious surface and corresponding storm-event volumes (Figure 6). Coal Creek, with an average impervious surface level of 23%, is an exception to this pattern. There is a higher maximum discharge per hectare relative to its level of impervious surface in comparison to the other sites. This is likely due to its greater relief compared to the other stations, which results in a higher average precipitation level across its catchment. If there were more monitoring locations with similar physical characteristics, but lower levels of impervious surface (i.e., below approximately 20%), a “leveling” of stormwater runoff would be a likely expression of this overall relationship.

Another exception among the monitoring locations is Phantom Creek, where the storm-event yield may be abnormally low due to the influence of Phantom Lake. The 26 hectare lake, representing 13% of the catchment area, is situated lower in the catchment and provides considerable flow storage capacity. This is particularly evident, given that the storms sampled at Phantom Creek had greater rainfall levels than most of the other stations.

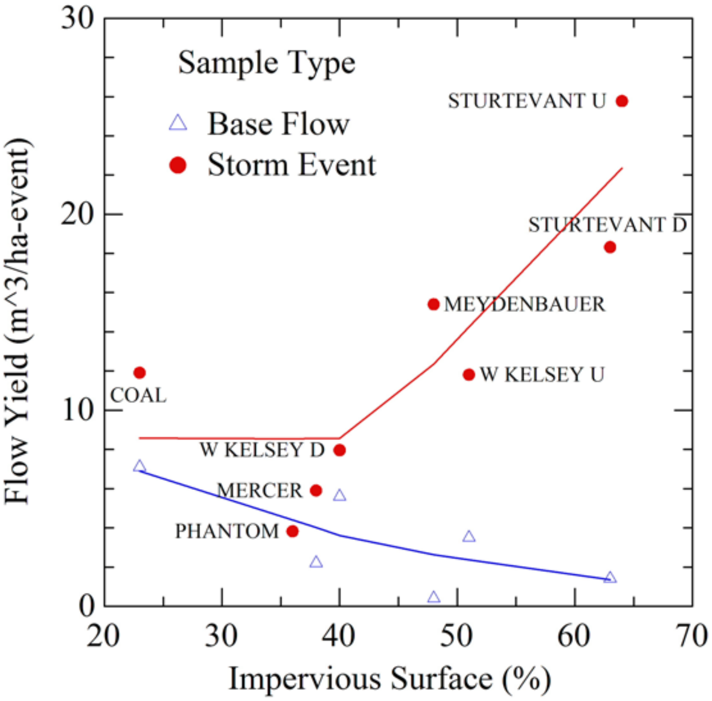

Figure 6. Impervious surface levels versus median storm-event and base-flow yields.

As shown in Figure 6, the sampled storm-event yield, at the 40% impervious surface level, is about 10 m^3/ha, while at 60% it is around 20 m^3/ha, or a 5 m^3/ha increase per 10% increase in the average impervious surface level. Considering the median daily rainfall event sampled, which was overall about 7 mm when applied over a one-hectare area, this level is 70 cubic meters of potential runoff. Allowing that flows for the Bellevue study represent only 6 hours of discharge, while the average storm event is about 11 hours, then at 40% and 60% impervious surface levels the storm-event yield is (subtracting an overall base-flow discharge of about 2 m^3/ha) approximately 16 m^3/ha and 35 m^3/ha, respectively. This indicates that at a 40% impervious surface level the effective runoff level is about 23% of the potential precipitation volume, while at 60% it is about 50%. Therefore, a 20% increase in the impervious surface level, through this range, results in a doubling of the runoff volume.

During base-flow conditions, there is a slight decline in median-normalized flow with increased impervious surface levels. Depending on regional infiltration and groundwater flow patterns, it is not uncommon that as impervious surface levels increase in a catchment, and more precipitation is directed to surface runoff and less directed to ground water, the base-flow levels in surface waters decline. The overall median base-flow yield among the monitoring stations is 2.2 m^3/ha-event.

Examination of Flow Estimates

Among the monitoring locations, both Coal Creek and Mercer Creek have some record of continuous flow monitoring. The United States Geological Survey (USGS) has maintained a flow station on Mercer Creek since 1955, while the flow in Coal Creek was monitored by King County from 2002 to 2005, and previously by the USGS from 1964 through 1968. From these records, flow metrics were determined and compared with those generated from the Bellevue data, providing a check on whether Bellevue's base-flow and storm-event monitoring were representative of typical flow conditions.

The flow record from 1988 to 1993, spanning the study period, was used to evaluate flow at Mercer Creek. For Coal Creek, flow records that spanned the full year were considered for analysis, and included 1964 to 1967 and 2003 to 2004. For each of these stations, the record of flow was divided into two conditions: base flow and storm events.

The annual base-flow level was assumed represented by the median of the daily average discharge levels. From this method, the base-flow levels for Mercer Creek and Coal Creek were determined to be 0.31 m^3/s and 0.16 m^3/s, respectively. These base-flow levels were then subtracted from the record of daily average flow, respective to each station, in order to identify periods with excess runoff, indicative of a storm event. A storm event was identified when the level of excess runoff was greater than the assumed base flow.

From this flow separation, the median number of days that storm events occurred per year for Mercer Creek and Coal Creek is 91 and 98 days, respectively. (This is close to the 94 days assumed with this study's loading calculations.) Applying the base flow at a constant level throughout the year, normalized by catchment area, and adjusting for the 6-hour sampling period used by the Bellevue study, results in an event yield of 2.3 m^3/ha-event and 2.2 m^3/ha-event for Coal Creek and Mercer Creek, respectively. While this base-flow yield is the same as that found during the study for Mercer, at Coal Creek it is about 75% lower. The base-flow level for 1964-1967 and 2003-2004 was 0.19 m^3/s and 0.16 m^3/s, respectively.

The storm-event yield, based on the total annual volume of storm-event runoff divided by the days of runoff occurrence, and adjusting for a 6-hour period (the same as that used in the original Bellevue study) and normalizing by catchment area, results in event storm flows for Mercer Creek and Coal Creek of 7.6 m^3/ha-event and 8.5 m^3/ha-event, respectively. For Coal Creek, this storm-event yield is about 29% lower than observed during the Bellevue study (11.9 m^3/ha-event), while that for Mercer Creek was about 29% higher (5.9 m^3/ha-event). Based on this fairly close agreement between the study median storm-event yields and those calculated from the flow record, these results indicate that overall sampling conditions were fairly representative of typical runoff conditions.

Worth mentioning here is that at increasingly higher impervious surface levels and greater runoff volumes, progressively greater source levels of pollutants are required to maintain even a constant concentration level in receiving waters. The inter-relationship between runoff, pollutant concentrations and loads will be developed further through the discussion of various pollutant indicators.

pH

The pH levels observed during storm events, across all impervious surface levels, were lower than observed during base-flow conditions (Figure 7). This is not surprising. Having reacted with atmospheric carbon dioxide, rain is naturally acidic with an average pH level of approximately 5.6. Increased impervious surface levels lower transit times from when rain falls to the ground to when it enters surface waters, resulting in less time for modification of pH associated with organic and inorganic influences (the reason why higher pH levels are observed at base-flow conditions).

As impervious surface levels and runoff volumes increase, pH levels decline. For a given impervious surface level, during storm events pH is about 0.3 units lower than observed during base flow. During storm events, pH levels at about the 20% impervious surface level were 7.7, declining to about 7.3 at 65%.

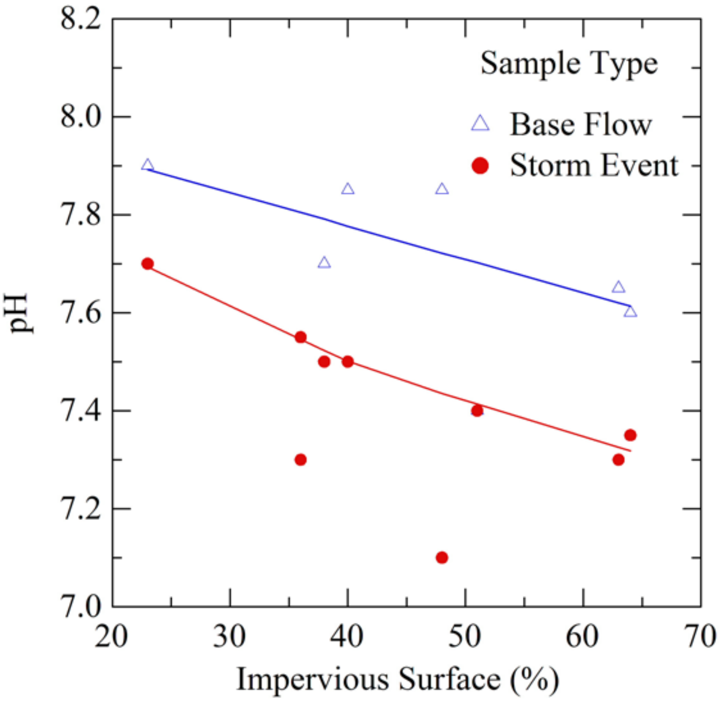

Figure 7. Impervious surface levels versus pH.

The level of flow is an important factor affecting pH levels. During storm events, as impervious surface levels increase, more of the stream flow is the result of direct surface runoff, while under base-flow conditions groundwater discharge is the primary source of flow.

This relationship is more clearly presented in Figure 8, where the best fit line (least square regression) between flow and pH is presented. The flows are all based on storm-event sampling. For the majority of the stations, pH levels decline with increased flow. The exception is Phantom Creek, though its primary flow source, Phantom Lake, is the major factor influencing its pH. pH levels at Meydenbauer (average impervious surface level of 48%), which receives drainage from Bellevue's central business district, are considerably lower than observed at the other monitoring locations. This reflects faster runoff transit times with less natural physical and biological interaction.

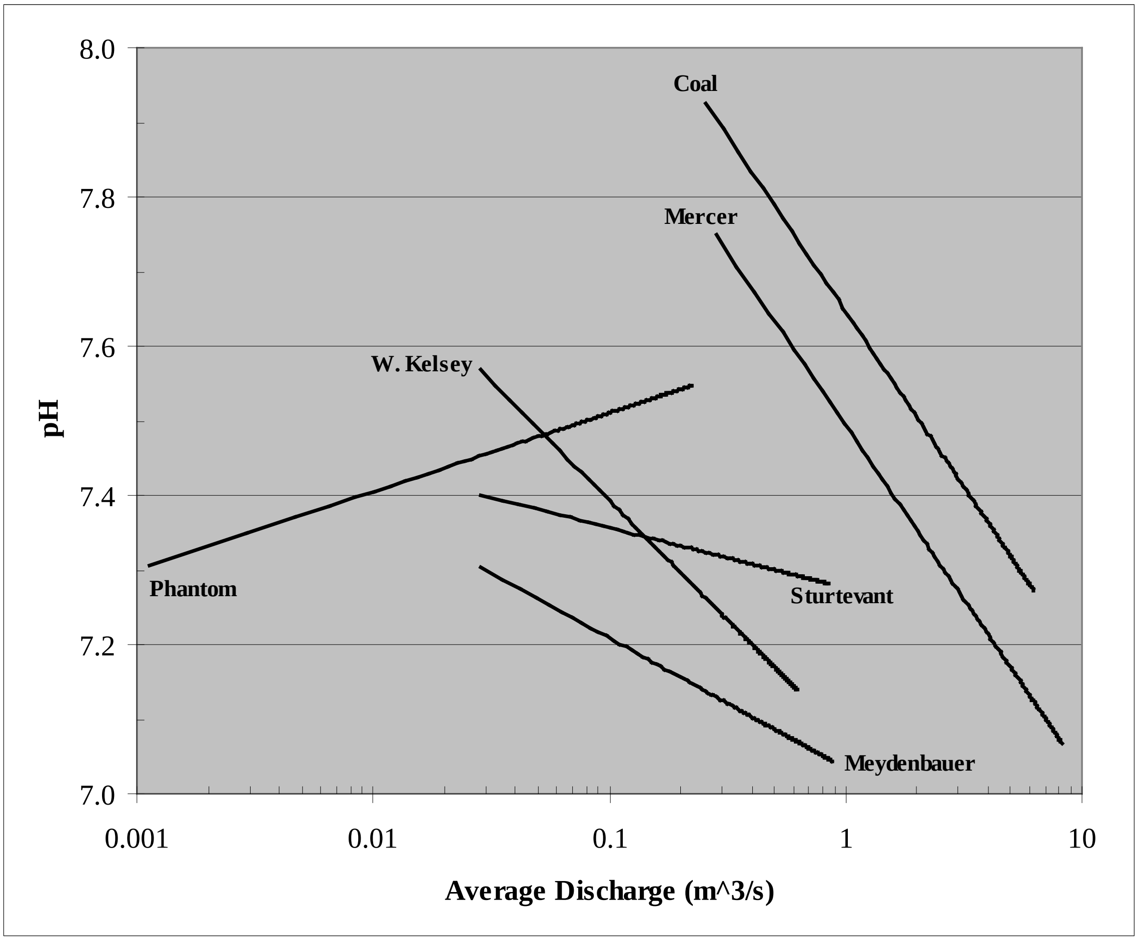

Figure 8. Relationship between discharge (m3/s) and pH during storm events.

Conductivity

Variation in impervious surface levels appears to have little effect on conductivity levels for either the base-flow of storm-event conditions (Figure 9). However, differences are present in the magnitude of conductivity when the base-flow and storm-event levels are compared. Similar to what was observed for pH, base-flow conductivity levels are greater than those observed during storm events. This is a reflection of the greater representation of groundwater discharge comprising stream flow at base conditions. Conductivity levels in ground water, as opposed to surface water, tend to be greater due to the dissolution of minerals. In contrast, storm-event runoff is largely comprised of recent precipitation, particularly at increased impervious surface levels. These relationships are presented in Figure 10 through the association between hardness and conductivity for the base and storm flow conditions.

As discussed previously, as impervious surface levels increase so does the amount of direct runoff to receiving waters, because there are less interception or storage pathways present. With lower opportunity for mineral dissolution at higher runoff levels, surface-water (stormwater) inflow is diluting groundwater-based conductivity. Storm-event conductivity levels are about 120 umhos/cm, rising at base flow to approximately 240 umhos/cm. While it appears that the greater surface runoff yield that occurs with increased impervious surface has little effect on conductivity levels, the fact that levels at base flow are greater indicates that the dominant source of flow does.

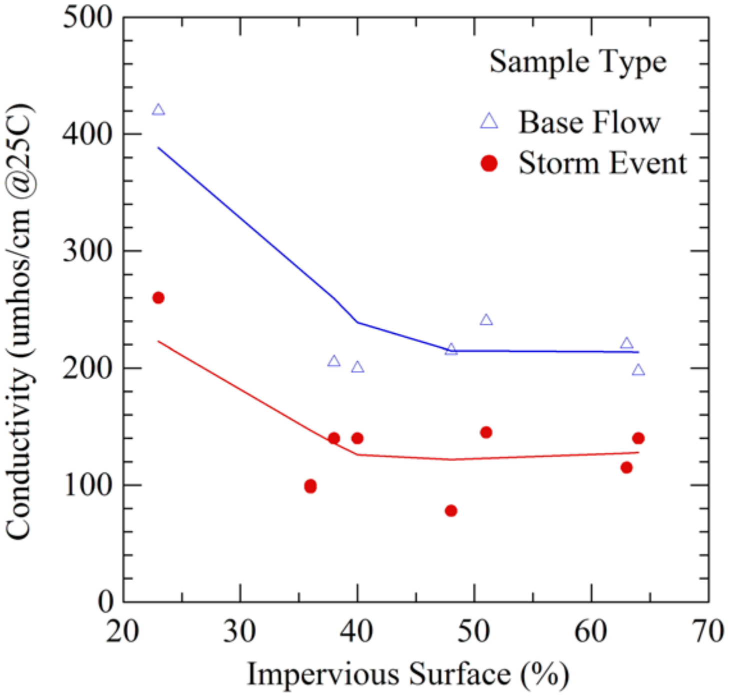

Figure 9. Impervious surface levels versus conductivity (μmhos/cm).

When the entire dataset of storm-event flow and conductivity are considered for each station, it is apparent that the primary factor controlling the variation in conductivity is the variation in flow, itself a function of its source (Figure 11). At low flow (base-flow conditions) ground water serves as the primary flow source. During these periods, conductivity levels are at their peak, reflecting the mineral dissolution that occurs within ground water. As base flows decline, older ground water with higher ion content are discharged to streams, while at higher flows a greater proportion of discharge is comprised of direct surface runoff with significantly lower ion content and, therefore, conductivity.

As observed in Figure 11, each of the monitoring stations has a characteristic relationship between the level of flow and conductivity. However, the majority of the stations share a similar overall relationship, despite differences in flow. This is indicated graphically by their sharing a common slope in their line of best fit. The exceptions are Phantom Creek and Coal Creek. Phantom Creek, which receives most of its discharge from Phantom Lake, has a low range in conductivity compared to the considerably larger, and more geologically diverse, Coal Creek catchment.

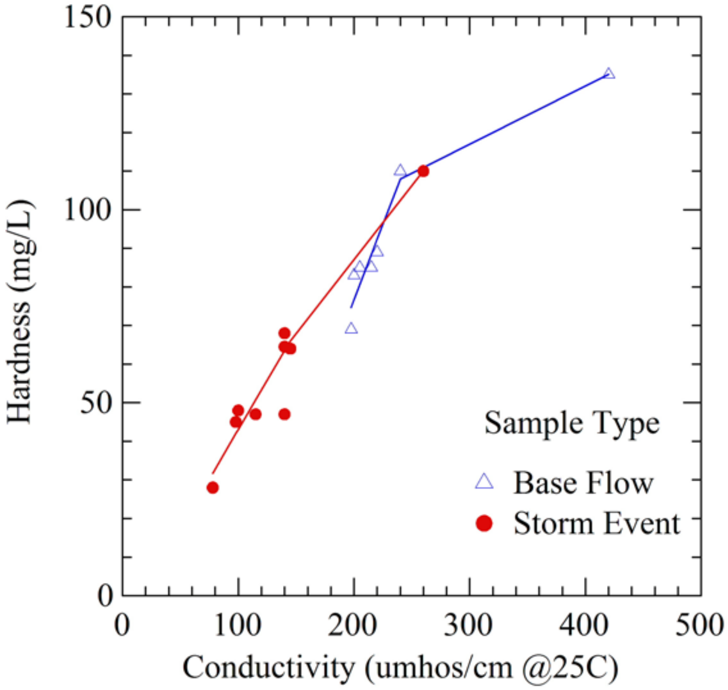

Figure 10. The relationship between conductivity (μmhos/cm) and hardness (mg/L).

Total suspended solids/turbidity

Both total suspended solids (TSS) and turbidity follow a similar pattern: low levels at base-flow conditions, significantly increasing during storm events (Figures 12 and 13). There does not appear to be any relationship between impervious surface levels and TSS or turbidity during either base-flow or storm-event conditions. While flow and impervious surface levels are positively correlated, this does not apply to turbidity and TSS. This may be the result of sampling methods that have not considered potential hysteresis effects. Within a particular storm event, TSS levels tend to increase as flow levels increase (through the rising limb of the hydrograph), though they have significantly lower levels, given the same flow level, on the falling limb of the hydrograph. The combined effect of averaging these concentrations throughout the storm event (method used by the Bellevue study), as a sample mean concentration, further reduces any potential relationship.

Another possible explanation as to why TSS concentrations do not vary with increased impervious surface levels is that there is a supply limitation. As more of the landscape is covered with impervious surfaces, there is less exposed soil effectively reducing potential surface erosion. In an urban environment, with a high representation of impervious surfaces, erosive energy is transferred from the land surface to the receiving surface water channel. However, if the stormwater impacts are advanced (i.e. the channel incision has already occurred) and measures to control bank erosion constructed, the channel could reach a new equilibrium to stormwater-related hydraulic changes. Such a situation could lead eventually to a stream channel sediment supply limitation.

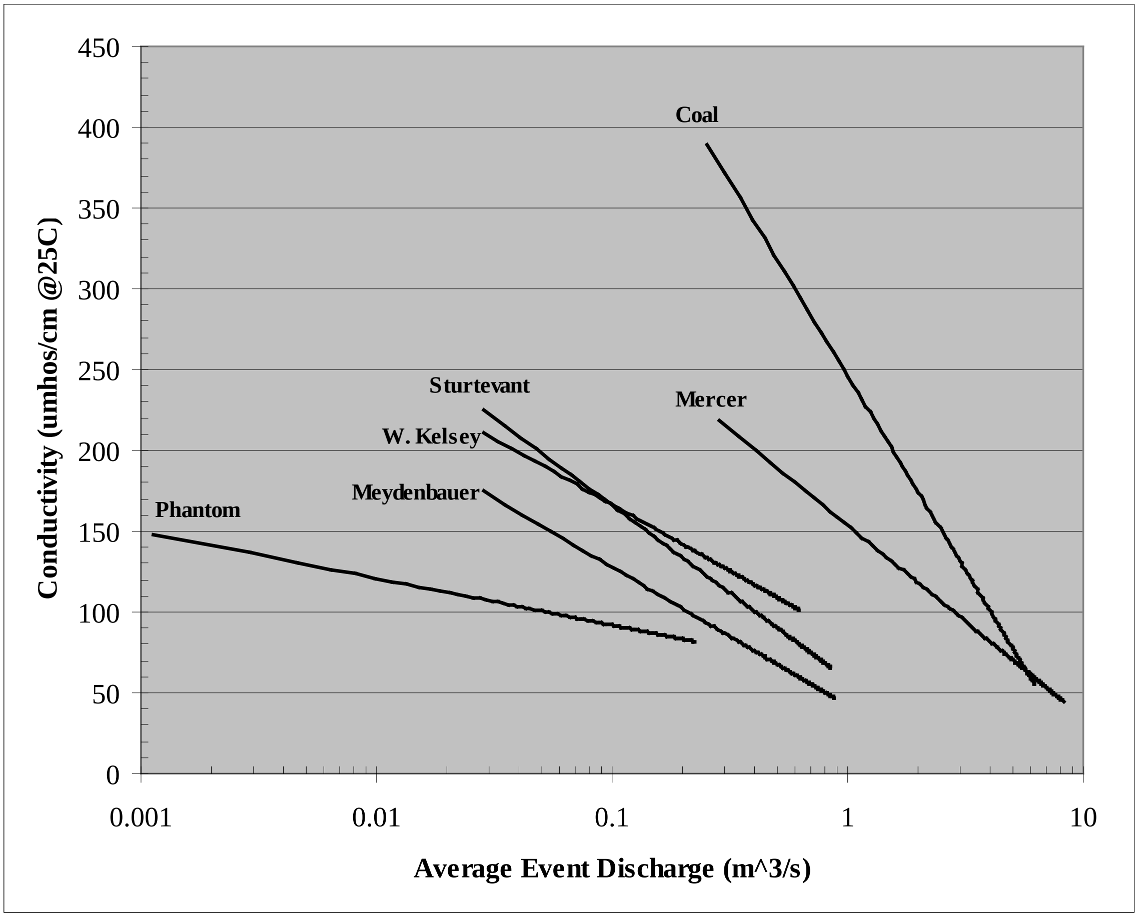

Figure 11. The relationship between discharge (m3/s) and conductivity.

For example, Coal Creek, though its catchment has the lowest average impervious surface level, has the highest median TSS and turbidity levels. (Coal Creek is an exception among the monitoring stations due to its size and relief.) In comparison, Mercer Creek has an average impervious surface level that is twice the level of the Coal Creek catchment, yet the median TSS concentration is 75% less. Coal Creek may be an example of an urbanizing stream, while Mercer Creek is an example of a stream that has come to some form of equilibrium with urban hydraulic influences.

As observed, for all monitoring streams there is an increased level of suspended sediment mobilized by stormwater runoff compared to the base-flow condition. So there are, of course, still flow-related influences. From Figures 12 and 13, at base-flow conditions TSS and turbidity levels are low at approximately 2.6 mg/L and 3.1 nephelometric turbidity units (NTU), respectively. During storm events, sediment is both transported to and within the streams at greater levels, in turn affecting turbidity levels. Average TSS and turbidity levels during storm events are 80.9 mg/L and 28.8 NTU, respectively.

When the TSS yield (kg/ha-yr) associated with storm events is considered, there is a stronger relationship with impervious surface levels (Figure 14). The reason is that in order to maintain uniform concentrations despite increased impervious surface levels (and therefore increased runoff volume), successively greater sediment yields are required. (Concentrations are maintained, countering the effect of dilution.)

Again, the exception among the stations is Coal Creek. Though having the lowest average impervious surface level among the monitoring locations, TSS concentrations and yields for Coal Creek are significantly greater than the other stations, the result of erosion processes present within the catchment. Primary sources contributing elevated levels of sediment to Coal Creek include stormwater runoff from Newport Hills, a residentially-developed area located in the lower portions of the catchment, and fill associated with historic mining activity deposited along sections of the stream bank in the catchment's upper portions (Bellevue, 1986).

For the other monitoring locations, there is a positive relationship between impervious surface levels and TSS yields, rising from about 20 kg/ha-yr at 35% impervious surface average to about 210 kg/ha-yr at a 65% average impervious surface level.

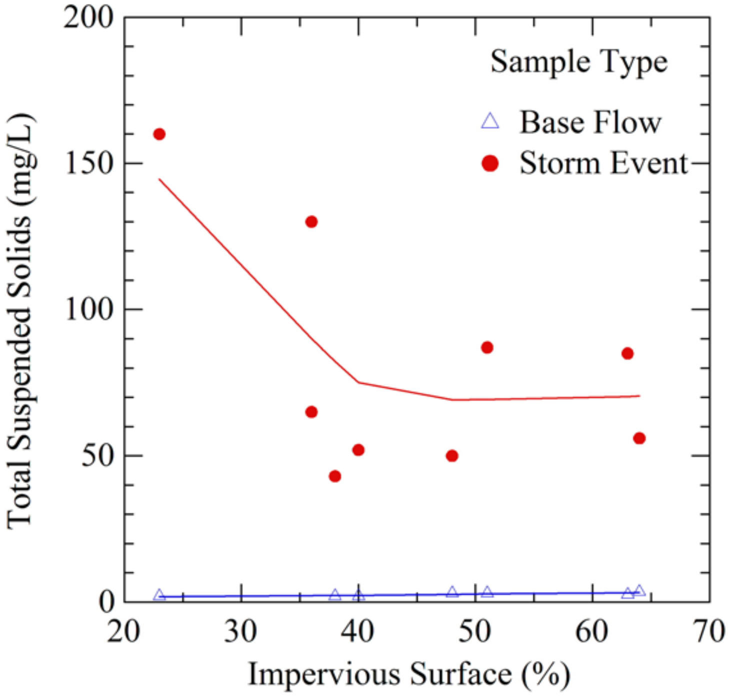

Figure 12. Total suspended solids (mg/L) versus impervious surface.

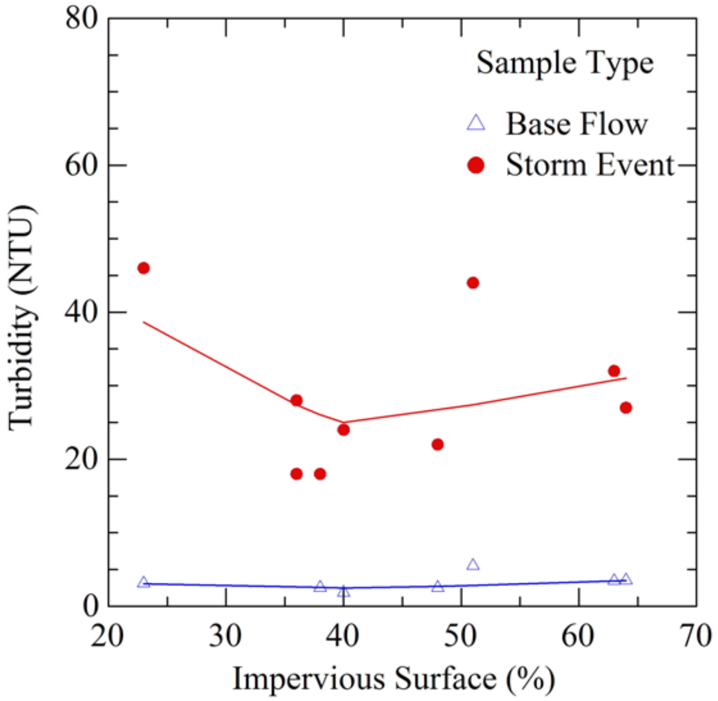

Figure 13. Turbidity (ntu) versus impervious surface.

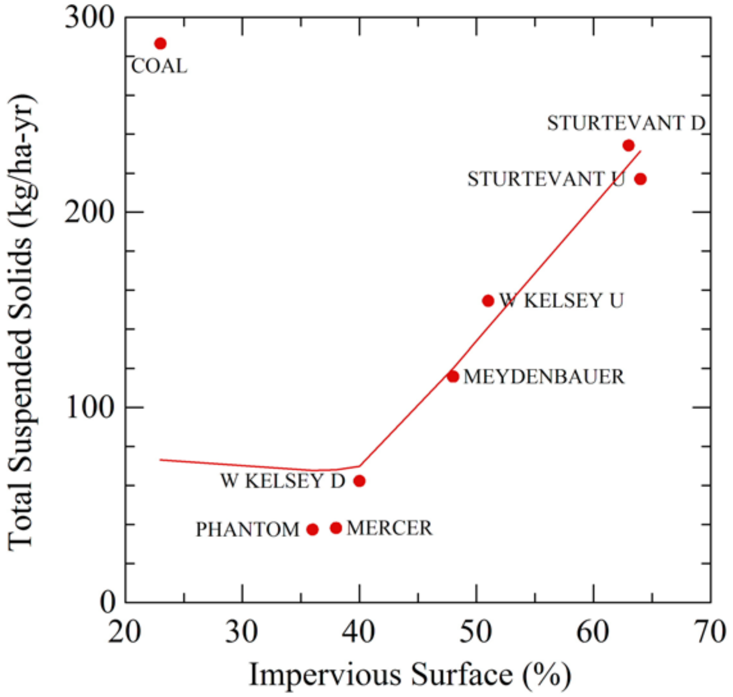

Figure 14. Impervious surface versus total suspended solids yield (kg/ha-yr).

Fecal coliform

At base flow, fecal coliform bacteria concentrations (associated with the waste of warm-blooded animals) are relatively uniform at about 200 colony forming units per 100 milliliter (cfu/100 ml) across the range of impervious surface levels. In contrast, during storm events there is a wide range in fecal coliform concentrations. Storm-event concentrations have an inverse relationship to impervious surface levels. Although bacteria levels are greatest at low impervious surface levels (primarily due to elevated levels observed in Coal Creek), and appear to decrease sharply as impervious levels increase, in reality, there is too much variability among the monitoring locations to consider any particular relationship present.

However, some of the lowest fecal coliform concentrations were observed at the highest impervious surface levels. This is counter-intuitive, as one would assume that at higher impervious surface levels and corresponding greater stormwater runoff, bacterial concentrations would increase, a relationship common with many of the water quality parameters examined. One possible explanation for this quite different relationship is dilution. As discussed previously, progressively higher impervious surface levels generate higher runoff volumes (normalized by area). Assuming an approximately uniform level of fecal coliform sources across the study area, then catchments with high impervious surface levels would have the effect of diluting bacterial sources through increased stormwater runoff volume. In other words, in order for bacterial concentrations to increase at higher runoff levels, progressively higher source levels are required. The supply cannot be limited.

Another explanation for this relationship is that the supply of fecal coliform bacteria is higher in locations with lower impervious surface levels. A higher bacterial supply and lower runoff volume results in increased bacterial concentrations in receiving waters. This scenario is suggested by the difference in bacterial concentrations observed at base-flow and storm-event conditions. The relative change in bacterial concentrations is significantly greater at low impervious surface levels than at sequentially higher ones. In fact, at the highest impervious surface levels there are relatively little differences in bacterial concentrations between the base-flow and storm-event observations. To be sure, there is a lot of variability in the bacteria data, and further monitoring would be required to determine whether there is validity to these possible explanations.

When the storm-event bacterial data are examined as a yield, there appears to be little relationship to varying impervious surface levels (Figure 16).

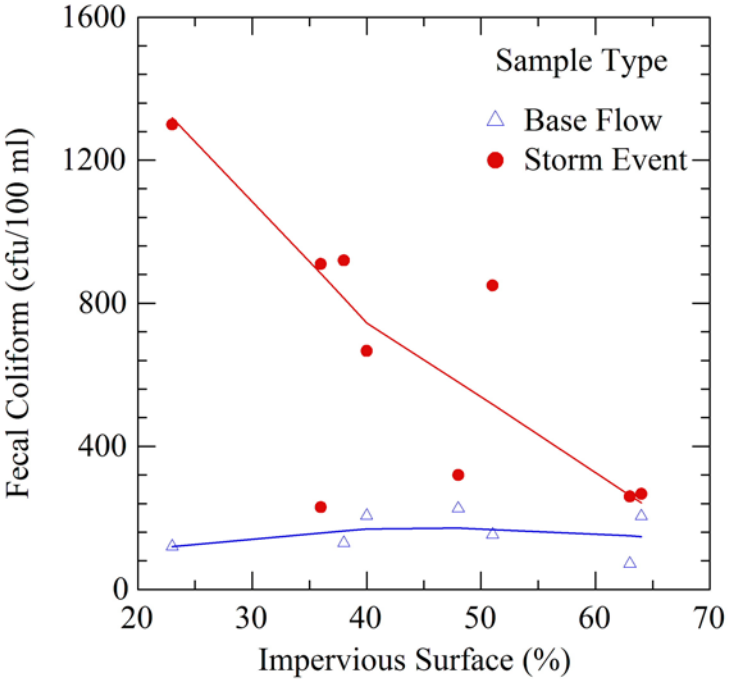

Figure 15. Impervious surface versus fecal coliform levels (cfu/100 ml).

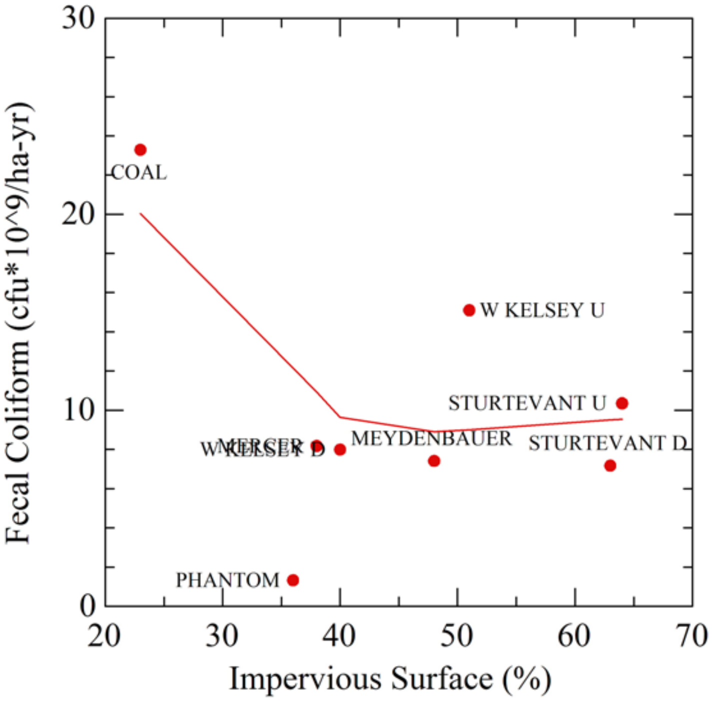

Figure 16. Impervious surface versus fecal coliform yield (cfu*109/ha-yr).

Total and ortho-phosphorus

Total phosphorus (TP) includes phosphorus in organic (i.e. phytoplankton) and inorganic forms (i.e. adsorbed to sediment) in addition to that found dissolved within the water (ortho-phosphate).

From the monitoring data, TP concentrations increase with increasing levels of impervious surface for both the base-flow and storm-event samples (Figure 17). Through the range in impervious surface levels, TP concentrations observed during storm events were greater, when compared to base-flow levels, by a factor of 10.

Whereas the overall median TP concentration increases from about 72 ug/L at base flow, to 170 ug/L during storm events, ortho-phosphate concentrations remain similar at 54 ug/L and 58 ug/L, respectively (Figure 18). This indicates that the majority of total phosphorus, about 75%, is in a dissolved form (ortho-phosphate) at base flow. Its representation decreases to about 34% during storm events, when the majority of the phosphorus is likely adsorbed to suspended sediment particles (Figure 19).

Similar ortho-phosphate concentrations were observed for both storm-event and base-flow monitoring. Both sample types display similar increases (slopes) in concentration with increasing impervious surface levels.

When examined on a yield basis (kg TP/ha-yr) both TP and ortho-phosphate display a strong positive relationship with impervious surface levels (Figures 20 and 21).

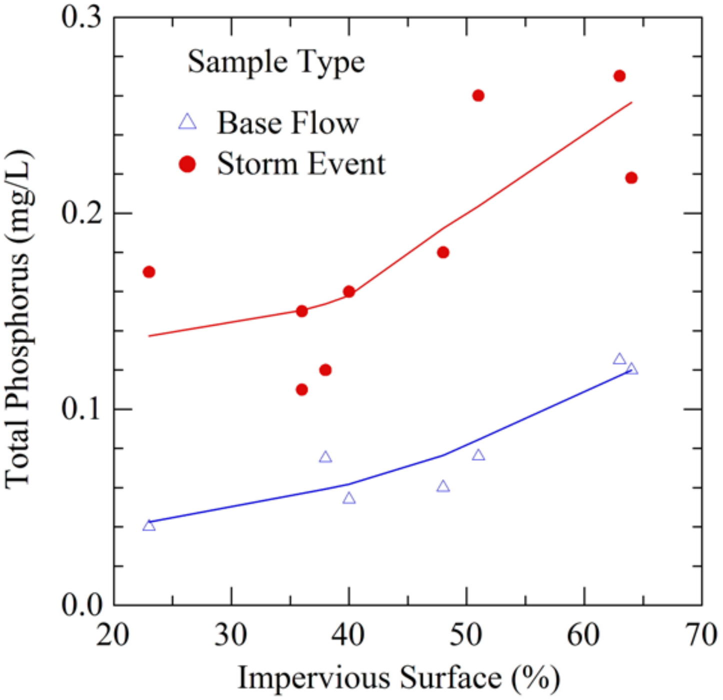

Figure 17. Impervious surface versus total phosphorus (mg/L).

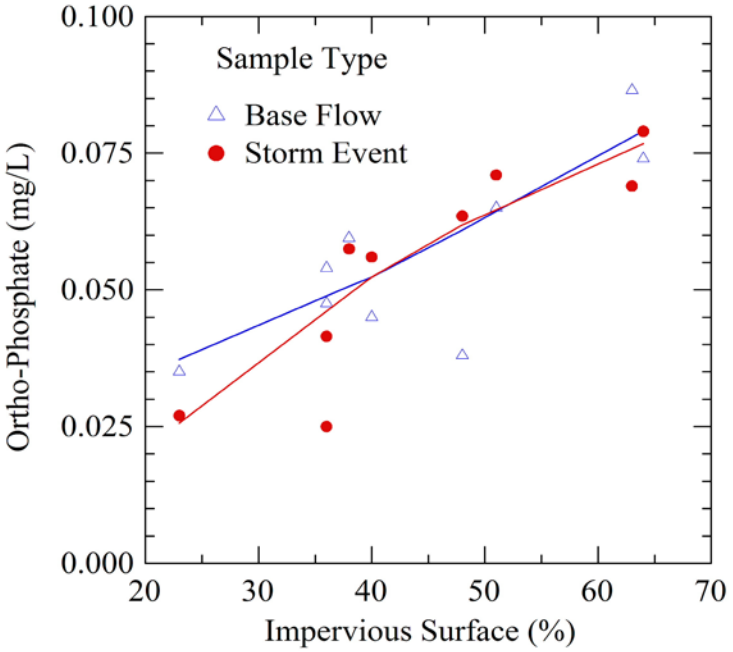

Figure 18. Impervious surface versus ortho-phosphate (mg/L).

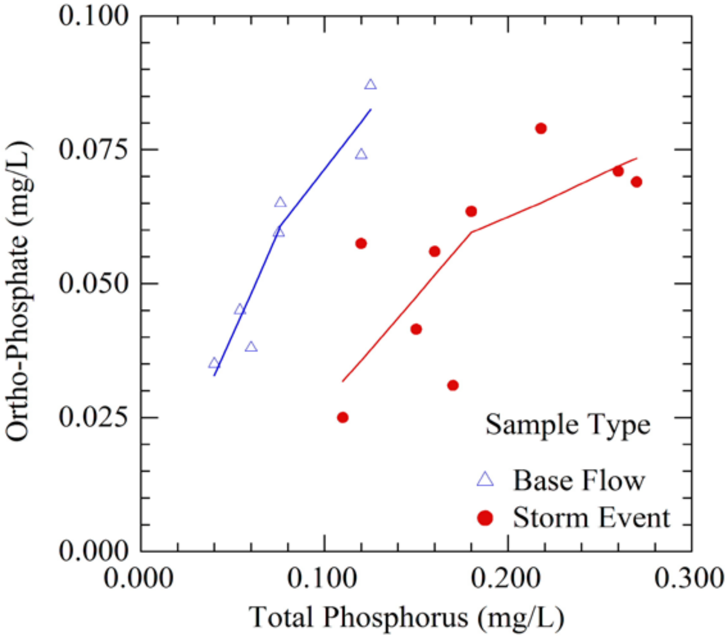

Figure 19. The relationship between total phosphorus and ortho-phosphate (mg/L) phosphorus (mg/L).

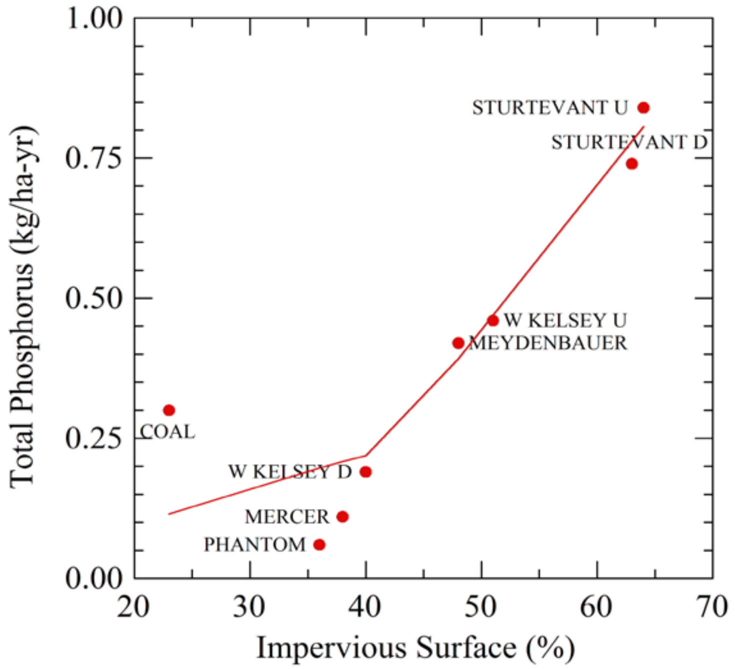

Figure 20. Impervious surface versus the annual total phosphorus yield (kg/ha-yr).

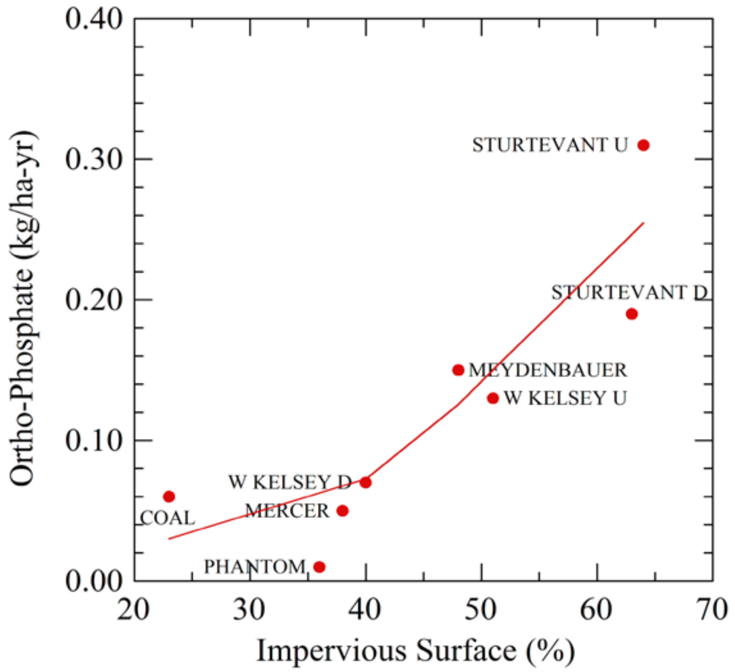

Figure 21. Impervious surface versus the annual ortho-phosphate yield (kg/ha-yr).

Nitrate – nitrite/ammonia

In surface waters receiving nonpoint source pollution runoff, ammonia is usually found in low concentrations. In fact, its presence at high concentrations is an indication of recently introduced waste, because under aerobic conditions it is rapidly oxidized into nitrite and then nitrate. Nitrate is the dissolved form of nitrogen typically found at the highest concentration within surface and ground water.

From the full dataset, when the concentration of nitrate-nitrite are plotted against concentrations of nitrate it is observed from the approximate 1:1 relationship that nitrate is the dominant form (Figure 22).

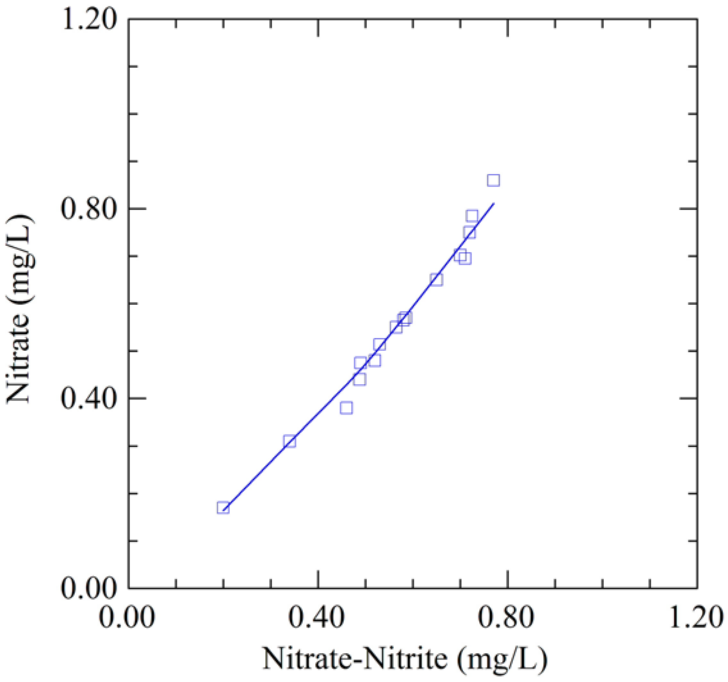

Figure 22. The relationship between nitrate-nitrite and nitrate (mg/L).

Ground water can be a substantial reservoir of nitrate, particularly in areas having undergone the relatively recent transition from rural/suburban to urban, such as Bellevue. For instance, farm animal wastes leaching to ground water, a significant nitrate source when land use was rural, could be supplanted by on-site wastewater systems following the transition to sub-urban residential development. With urbanization and the centralization of wastewater treatment, the nitrate supply may actually diminish, resulting in lower groundwater concentrations. This situation may be the case with Bellevue.

Nitrate-nitrite concentrations, observed during base-flow and storm-event monitoring, decrease with increasing impervious surface levels (Figure 23). In addition, storm-event nitrate-nitrite concentrations are lower than observed at base flow. While differing in absolute concentrations, both datasets display a similar slope or change in concentration through variation in impervious surface levels. Many of these relationships are shared with the water quality parameters pH and conductivity. For these parameters, the relative contribution of groundwater discharge comprising stream flow is the primary determinant on receiving water concentrations.

From the storm-event dataset, that nitrate-nitrite concentrations decline slightly as impervious surface levels increase indicates that the nitrate supply is limited. Concentrations become diluted as impervious surface and, therefore, runoff levels increase. This is indicated by the fact that base-flow concentrations tend to be slightly higher, a characteristic shared with pH and conductivity. That these datasets are congruent in their relation to impervious surface levels indicates that they share a common source, ground water. This is supported by Coal Creek, which has a greater portion of storm-event flow represented by groundwater discharge in comparison to the other stations. It also has among the greatest base-flow and storm-event nitrate concentrations.

While concentrations decline with increased impervious surface levels during storm events, the overall yield of nitrate-nitrite increases with increased impervious surface levels (Figure 24).

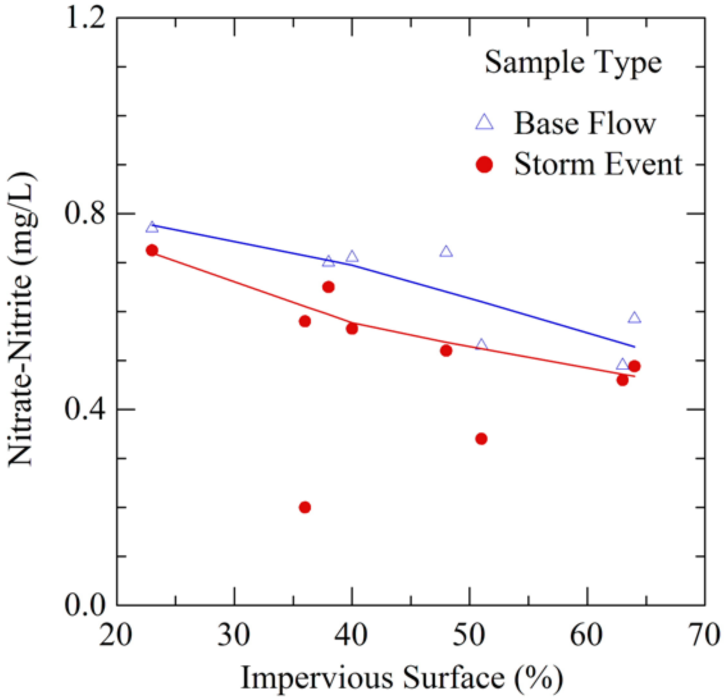

Figure 23. Impervious surface level versus nitrate-nitrite concentrations (mg/L).

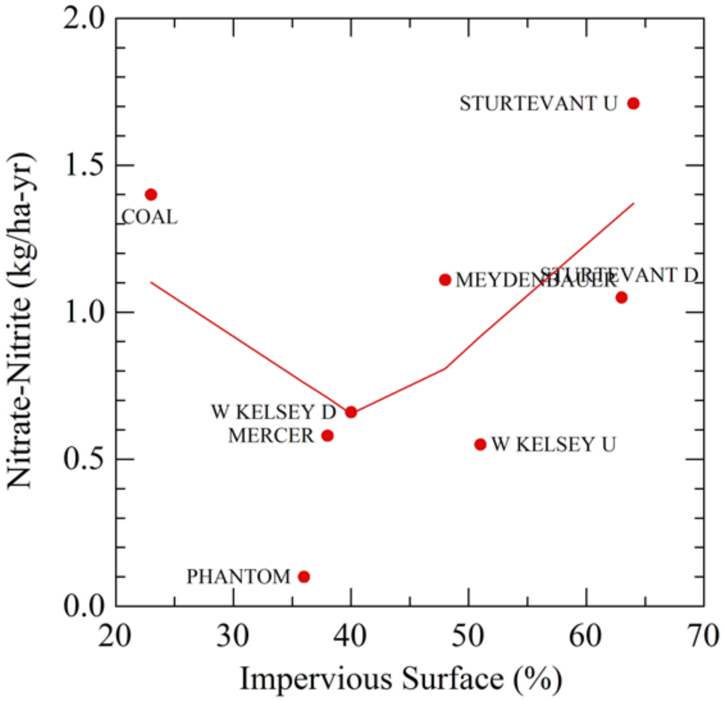

Figure 24. Impervious surface level versus the annual nitrate-nitrite yield (kg/ha-yr).

Ammonia is an indicator of fresh waste and is typically found in ground water at very low concentrations. At base-flow conditions, ammonia concentrations were relatively uniform through varying impervious surface levels at around 0.05 mg/L (Figure 25). In contrast to nitrate, ammonia concentrations during storm events increased with increased impervious surface levels. As the storm-event yield increases, ammonia concentrations also increase. For this reason, there is a strong positive relationship between ammonia levels, calculated as a yield (kg/ha-yr), and average catchment impervious surface levels (Figure 26).

Within the urban environment, ammonia concentrations observed in receiving waters are driven by the level of storm-event runoff, as opposed to nitrate, where the supply is driven by the amount of groundwater discharge. An example of this is Coal Creek, where groundwater discharge is highly represented, even during storm events. As a consequence, nitrate concentrations and yields tend to be more elevated. Given its relatively low impervious surface level in comparison to the other stations, and therefore storm water runoff, Coal Creek has among the lowest ammonia concentrations and yields.

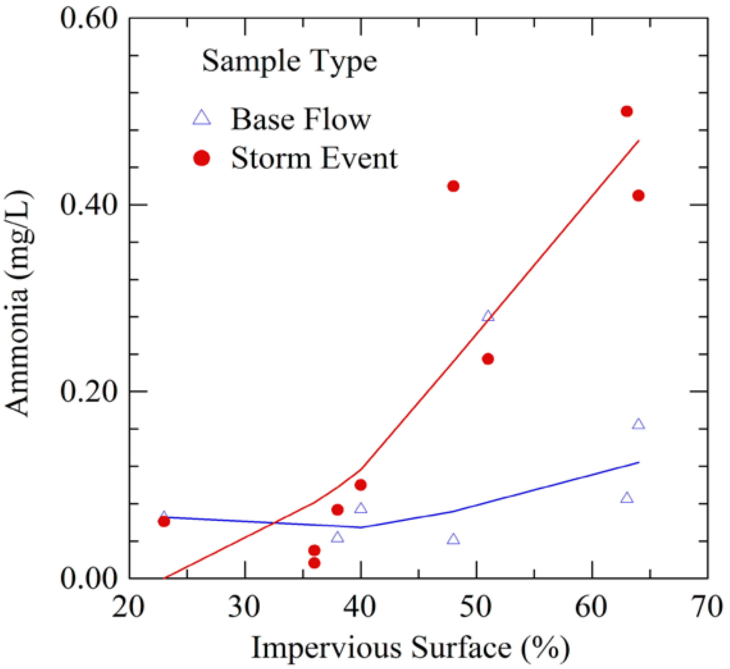

Figure 25. Impervious surface level versus ammonia concentrations (mg/L).

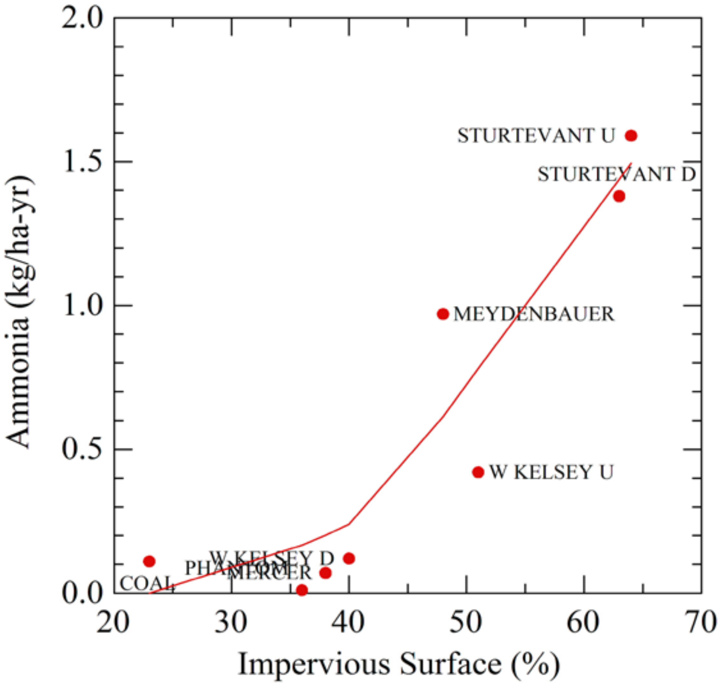

Figure 26. Impervious surface level versus annual ammonia yields (kg/ha-yr).

Chemical oxygen demand

Chemical oxygen demand (COD) is a measure of the total quantity of chemically oxidizable material present in the water column, and is therefore a general indicator of impacts to dissolved oxygen by pollutant loading. Reduced carbon compounds are found throughout nature and are the dominant sources of COD in natural aquatic systems. They include animal and vegetable fats and lipids, carbohydrates, sugars, and proteins. In an urban setting such as Bellevue, additional COD sources include petroleum hydrocarbons. In fact, oils and greases, which are comprised primarily of total petroleum hydrocarbons (TPH), appear to be an important source of storm-event related COD in Bellevue's streams (Figure 27).

As observed, at base-flow conditions COD levels are uniform at about 15 mg/L through the range in impervious surface levels examined, and represent a background condition for these waters (Figure 28). However, during storm events receiving water COD concentrations increase with increasing impervious surface levels, indicating that surface-water runoff is a driving factor.

Figure 29 relates the median storm-event flow yield to COD concentrations. As flow levels increase (with increased impervious surface levels), so do COD concentrations. The underlying association is that increased runoff, corresponding to higher impervious surface levels, results in transporting higher levels of organic material to surface waters. So, the supply of organic material is only limited by the ability of surface runoff to both deliver organic material to and transport it within receiving waters. This is further indicated by the strong relationship between the COD yield (kg COD/ha-yr) and impervious surface levels (Figure 30).

Among the monitoring stations, the concentration of COD observed at Meydenbauer (average impervious surface level of 48%) during storm events is abnormally elevated. Meydenbauer receives storm runoff from Bellevue's central business district, and likely much of the demand is related to total petroleum hydrocarbons levels. The detected levels of total petroleum hydrocarbons at Meydenbauer were the highest among the monitoring locations (refer to Table A-1).

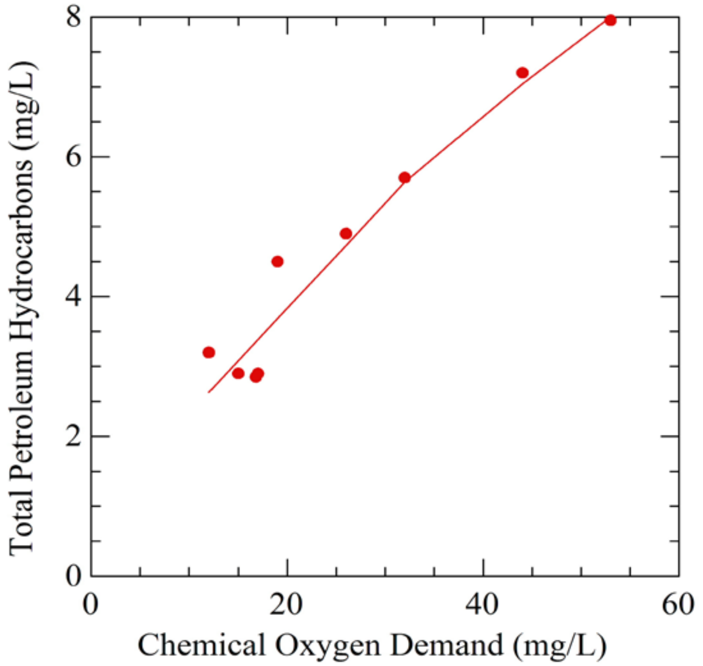

Figure 27. COD (mg/L) versus TPH (mg/L) during storm events.

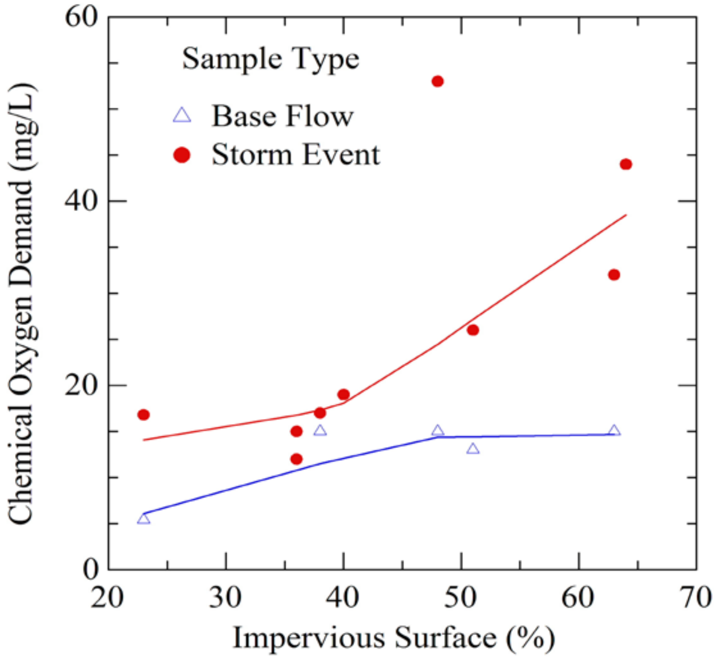

Figure 28. Impervious surface levels versus COD (mg/L).

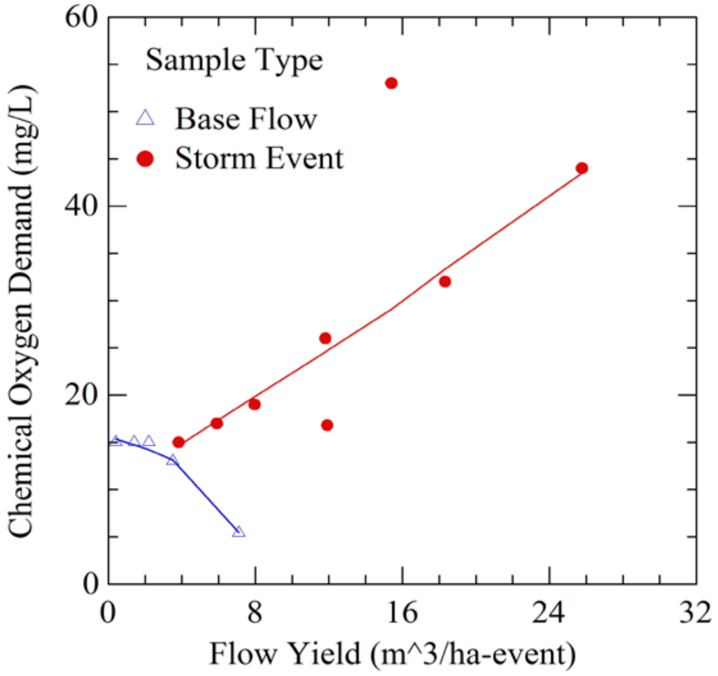

Figure 29. Flow yield (m3/ha-event) versus COD (mg/L).

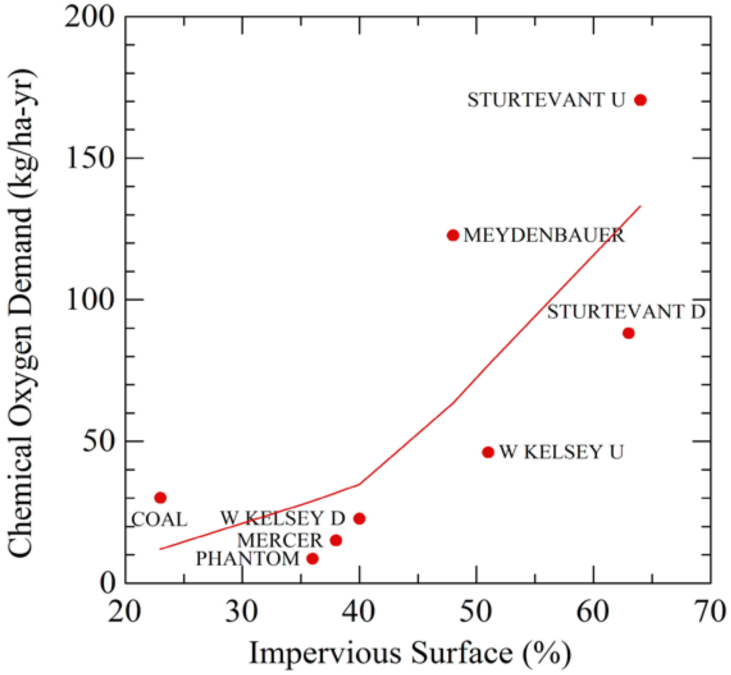

Figure 30. Impervious surface levels versus annual COD yield (kg/ha-yr).

Metals

Bellevue's stormwater monitoring included the analysis of lead, zinc, cadmium, chromium, nickel, and copper. All these metals occur naturally, though are typically observed at more elevated concentrations in urban settings. This is due primarily to automobile use as well as manufacturing processes. As discussed earlier, no more than 30% of total observations (by station and parameter) were to be reported as below the detection level if any analysis were to occur. Among the metals examined, lead, cadmium, nickel, and chromium were often below their respective detection limits for many of the monitoring locations (refer to Appendix A). However, both zinc and copper were consistently reported for all monitoring locations and were analyzed consistent with previous analysis methods. Median metal concentrations for the various monitoring locations that met the reporting criteria are presented in Table 3.

The relationship between impervious surface levels and the concentrations and yields of zinc and copper are presented in Figures 31-34. Among the stations, the overall median base-flow zinc and copper concentrations were observed at 40 ug/L and 10 ug/L, respectively. Both metals were detected at higher concentrations during storm events than at base-flow conditions. In particular, zinc concentrations rose sharply during storm events with increasing impervious surface levels. This is particularly evident when the yield versus impervious surface is considered. Similar, though less-defined relationships (due to increased variability) were observed for copper. During storm events, the zinc and copper concentrations observed in Bellevue's receiving waters are linearly related, which is likely attributed to their sharing similar sources and transport mechanisms (Figure 35).

A primary source for many of these metals is the automobile, and its influence on metal concentrations is particularly evident for lead (Table 4). Tetra-ethyl lead was a petrol additive until 1976, when the United States Environmental Protection Agency (EPA) began to phase out its use, completed by 1986. The median lead concentration detected in storm runoff in the early 1980s within two Bellevue catchments, Surrey Downs and Lake Hills, was 147 and 120 ug/L, respectively (Galvin, 1982; Table 4). By the mid-1990s, following the complete phase out of lead additive, levels had fallen significantly. Regardless of impervious surface level, the highest median lead level was observed at W. Kelsey U at 35 ug/L, about a 75% reduction from levels observed in the previous decade. The catchment with a comparable impervious surface level to those from the baseline studies is W. Kelsey D at 40%, where the median lead level of 14 ug/L was detected in storm runoff (Table 4).

Evident from Table 4 is that with the exception of lead, metal concentrations in Bellevue storm water have remained relatively steady from the early 1980s to the mid 1990s. For the others, metal concentrations detected in receiving waters have remained relatively consistent between the studies, indicating that the primary pollutant source (i.e. automobile) has maintained loading at a fairly steady rate over this period.

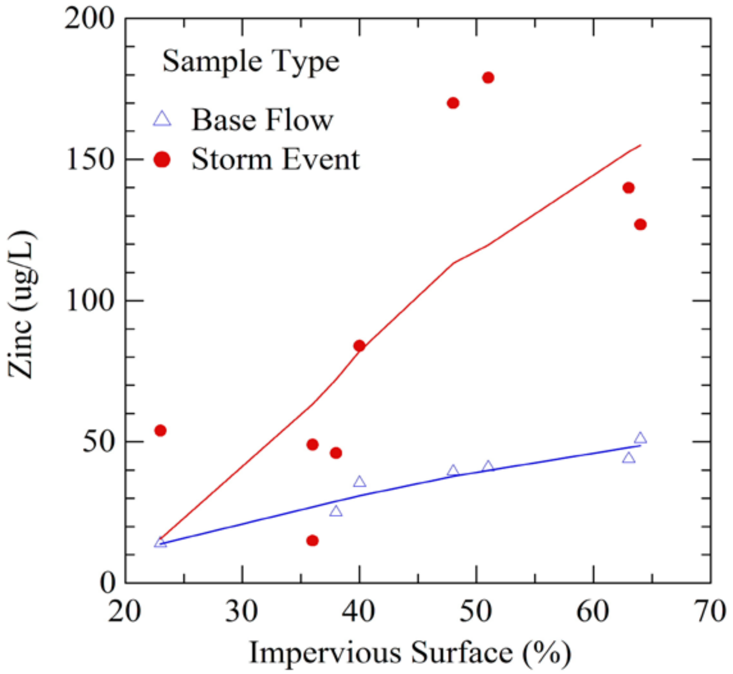

Figure 31. Impervious surface levels versus zinc concentrations (ug/L).

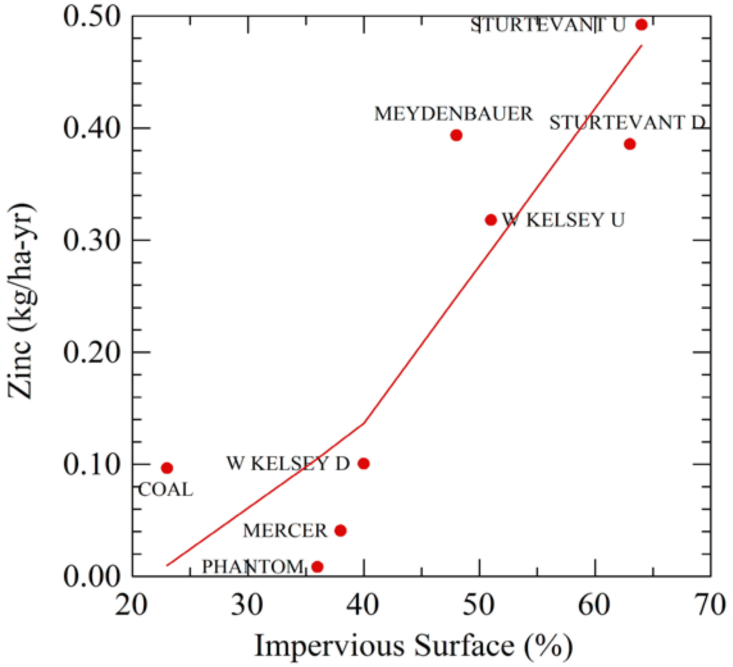

Figure 32. The relationship between impervious surface levels and annual zinc yields (kg/ha-yr).

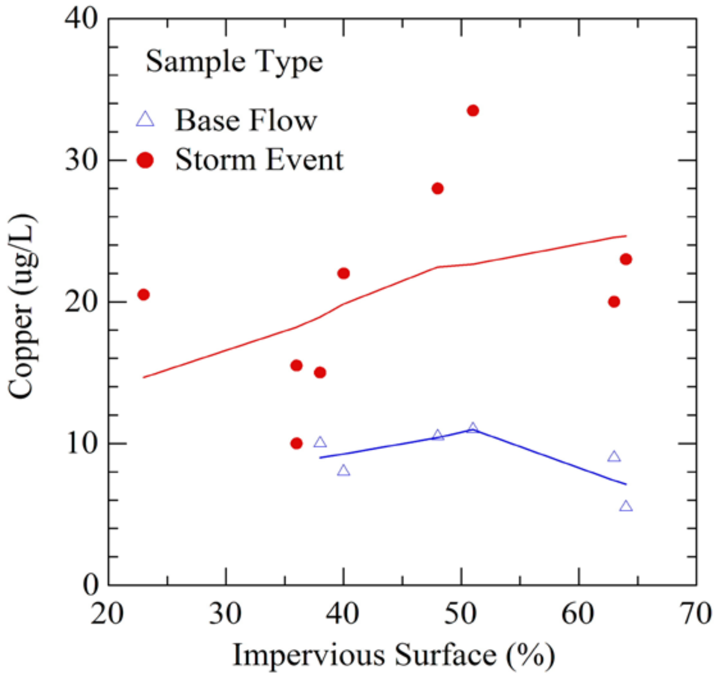

Figure 33. Impervious surface levels versus copper concentrations (ug/L).

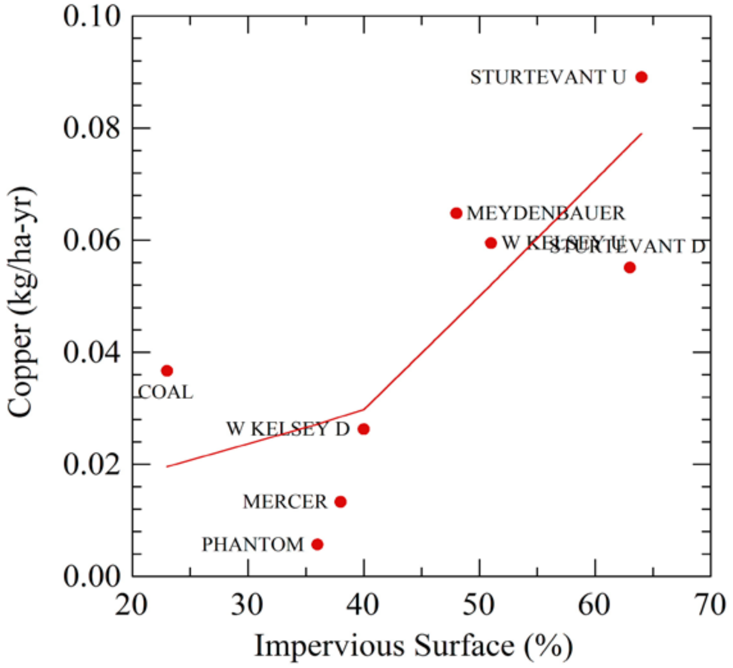

Figure 34. The relationship between impervious surface levels and annual copper yields (kg/ha-yr).

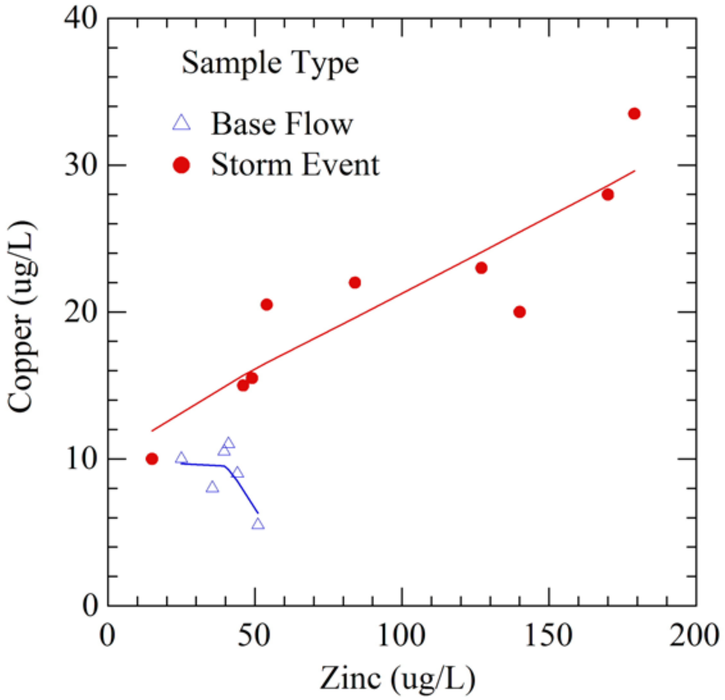

Figure 35. The relationship between receiving water zinc and copper concentrations (ug/L).

Table 3. Median concentrations (ug/L) and annual yields (kg/ha-yr) for various metals analyzed at Bellevue monitoring locations during storm events.

Stations	Lead		Cadmium		Zinc		Nickel		Chromium		Copper	
	Median Conc.	Yield	Median Conc.	Yield	Median Conc.	Yield	Median Conc.	Yield	Median Conc.	Yield	Median Conc.	Yield
W. Kelsey U	35.0	0.062	0.70	0.0012	179	0.318	11.0	0.020	>30% nd	==	33.5	0.06
W. Kelsey D	14.0	0.017	0.67	0.0008	84	0.101	5.5	0.007	>30% nd	==	22.0	0.026
Mercer	>30% nd	==	>30% nd	==	46	0.041	>30% nd	==	>30% nd	==	15.0	0.013
Coal	>30% nd	==	>30% nd	==	54	0.097	>30% nd	==	>30% nd	==	20.5	0.037
Meydenbauer	>30% nd	==	>30% nd	==	170	0.394	>30% nd	==	>30% nd	==	28.0	0.065
Sturtevant U	23.0	0.089	>30% nd	==	127	0.492	>30% nd	==	>30% nd	==	23.0	0.089
Sturtevant D	27.5	0.076	0.85	0.0023	140	0.386	9.0	0.025	>30% nd	==	20.0	0.055
Wilkins	>30% nd	==	n<4	==	49	==	>30% nd	==	12.5	==	15.5	==
Phanton	n<4	==	n<4	==	15	0.009	n<4	==	>30% nd	==	10.0	0.006

Shaded data= >30% of reported observations less than detection limit, table value is median of concentrations above detection limit.

<4 = reported observations number less than 4.

Table 4. Median concentrations (ug/L) of metals observed at Surrey Downs and Lake Hills in comparison to W Kelsey (d).

Parameter (ug/L)	Monitoring Locations		
	Surrey Downs(1)	**Lake Hills(1)**	**W. Kelsey (d)**
Lead	147 66-460 n=10	120 60-420 n=11	14 1-160 n=13
Zinc	101 40-250 n=10	70 28-240 n=11	84 7-330 n=13
Copper	16 5-46 n=10	20 4-28 n=11	22 10-79 n=12
Cadmium	0.5 0.2-1.3 n=10	0.6 0.1-1.9 n=11	0.7 0.2-2.0 n=12
Nickel	7 2-32 n=10	5 2-27 n=11	6 2-20 n=12
Chromium	8 2-19 n=10	5 2-16 n=11	7(2) 6-14 n=5

1. Reported in Galvin, 1982.
2. Reported values.

The average impervious surface level for Surrey Downs and Lake Hills is 40% and 35%, respectively.

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Conclusions

A common finding throughout this analysis is that as average catchment impervious surface levels increase, so do pollutant concentrations and yields observed in receiving waters. Driving this process is the positive association between the level of impervious surface and the volume of stormwater runoff.

With urbanization and the associated increased levels of impervious surface, former water interception and storage capacity present within vegetation, organic and inorganic soil layers, and shallow ground water is significantly reduced. The loss of this storage leads to the generation of stormwater runoff that requires collection and ultimately disposal, typically to a nearby surface water. As a consequence, urban streams receive stormwater inflow at an increased frequency, rate, and volume. These hydraulic changes result in receiving water channel incision and bank erosion, in addition to the introduction of a variety of pollutants. The end result is that the extent and diversity of aquatic habitats, present prior to urbanization, are largely lost. The observed relationships between impervious surface and sampled storm-event runoff yields indicate that Bellevue’s streams follow this pattern.

Associated with this increased runoff are a wide variety of pollutants. When pollutant concentrations, observed during storm events, are positively correlated to impervious surface levels, they also tend to be well correlated to the level of stormwater inflow. This is because as stormwater runoff increases, there is a corresponding increase in pollutant delivery to and transport within receiving waters. An indicator that runoff is a primary driver on pollutant levels is if concentrations at base flow show relatively little positive correlation to increasing impervious surface levels, while under storm events they do. From this analysis, two general relationships were found between parameter concentrations and impervious surface levels: one characterized as a supply limitation, and the other a flow or transport limitation.

A pollutant supply limitation is indicated where increased impervious surface levels and, therefore stormwater runoff, results in lower parameter concentrations observed in receiving waters. This is primarily the result of dilution. This scenario applied to the water quality parameters pH, conductivity, and nitrate, whose concentrations are influenced by the relative magnitude of groundwater discharge. These parameters tend to be observed at higher levels at base flow, when ground water comprises the major source of flow, as opposed to during storm events.

The most common relationship observed between pollutant concentrations and impervious surface levels is where there is a sufficient reservoir of pollutant available on the land surface that receiving water concentrations are only limited by stormwater transport capacity. In this situation, the pollutant supply exceeds the transport capacity. The greater the ability of excess runoff to mobilize the pollutant, as defined by increased runoff yield, the higher the receiving water concentration. So, while at greater impervious surface levels there is greater runoff volume, there is also greater pollutant loading offsetting the potential effect of dilution. For this reason, in terms of receiving water pollutant concentrations, this is described as a flow limitation scenario and it applies to the majority of pollutants examined in this analysis.

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Appendix A: Median Storm Event and Base-flow Parameter Levels

Table A-1. Median parameter values observed during storm events.

Monitoring Stations	Avg Q (cms)	Sample Volume (m^3*1000)	Max Q (cms)	pH	Conductivity (umhos/cm)	Hardness (mg/L)	Total Suspended Solids (mg/L)	Turbidity (NTU)	Chemical Oxygen Demand (mg/L)	Total Phosphorus (mg/L)	Ortho-Phosphate (mg/L)	Fecal Coliform (mpn/100 ml)	Oil and Grease (mg/L)	Total Petroleum Hydrocarbons (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrate+Nitrite (mg/L)	Ammonia (mg/L)	Lead (ug/L)	Cadmium (ug/L)	Zinc (ug/L)	Nickel (ug/L)	Chromium (ug/L)	Copper (ug/L)
W. Kelsey U	0.13	2.75	0.22	7.4	145	64	87	44	26.0	0.260	0.071	850	4.9	4.9	0.310	0.030	0.340	0.235	35.0	0.70	179	11.0	13.5	33.5
W. Kelsey D	0.21	4.59	0.25	7.5	140	68	52	24	19.0	0.160	0.056	667	4.5	4.5	0.550	0.020	0.565	0.100	14.0	0.67	84	5.5	7.0	22.0
Mercer	0.85	17.84	1.19	7.5	140	65	43	18	17.0	0.120	0.058	920	4.6	2.9	0.650	0.015	0.650	0.074	12.5	0.30	46	5.0	9.0	15.0
Coal	0.85	18.40	1.08	7.7	260	110	160	46	16.8	0.170	0.031	1300	4.0	2.9	0.780	0.014	0.725	0.061	6.0	0.30	54	9.5	14.0	20.5
Meydenbauer	0.20	3.11	0.51	7.1	78	28	50	22	53.0	0.180	0.064	320	11.0	8.0	0.480	0.036	0.520	0.420	25.5	0.90	170	11.0	9.0	28.0
Sturtevant U	0.21	3.77	0.29	7.4	140	47	56	27	44.0	0.218	0.079	267	7.6	7.2	0.440	0.047	0.488	0.410	23.0	0.92	127	7.0	9.0	23.0
Sturtevant D	0.23	4.25	0.64	7.3	115	47	85	32	32.0	0.270	0.069	260	8.2	5.7	0.380	0.044	0.460	0.500	27.5	0.85	140	9.0	12.0	20.0
Wilkins	==	==	==	7.3	98	45	130	28	12.0	0.150	0.042	910	4.3	3.2	0.565	0.008	0.580	0.030	40.0	<4	49	20.0	12.5	15.5
Phantom	0.04	0.76	0.04	7.6	100	48	65	18	15.0	0.110	0.025	230	3.0	2.9	0.170	0.040	0.200	0.017	<4	<4	15	<4	16.0	10.0

Shaded data= >30% of reported observations less than detection limit, table value is median of concentrations above detection limit.
<4 = reported observations less than 4.

Table A-2. Median parameter values observed at base flow.

Monitoring Stations	Avg Q (cms)	Sample Volume (m^3*1000)	Max Q (cms)	pH	Conductivity (umhos/cm)	Hardness (mg/L)	Total Suspended Solids (mg/L)	Turbidity (NTU)	Chemical Oxygen Demand (mg/L)	Total Phosphorus (mg/L)	Ortho-Phosphate (mg/L)	Fecal Coliform (mpn/100 ml)	Oil and Grease (mg/L)	Total Petroleum Hydrocarbons (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrate+Nitrite (mg/L)	Ammonia (mg/L)	Lead (ug/L)	Cadmium (ug/L)	Zinc (ug/L)	Nickel (ug/L)	Chromium (ug/L)	Copper (ug/L)
W. Kelsey (u)	0.04	0.82	==	7.4	240	110	3.0	5.5	13.0	0.076	0.065	154	<4	<4	0.514	0.016	0.530	0.280	3.0	<4	41.0	<4	<4	11.0
W. Kelsey (d)	0.15	3.23	==	7.9	200	83	2.0	1.9	<4	0.054	0.045	206	<4	<4	0.695	0.011	0.710	0.074	3.5	0.210	35.5	<4	<4	8.0
Mercer	0.31	6.74	==	7.7	205	85	2.0	2.5	15.0	0.075	0.060	130	<4	<4	0.702	0.007	0.700	0.043	2.0	0.145	25.0	<4	<4	10.0
Coal	0.51	11.04	==	7.9	420	135	2.0	3.1	15.0	0.040	0.035	120	<4	<4	0.860	0.005	0.770	0.065	<4	<4	14.0	<4	<4	<4
Meydenbauer	0.01	0.14	==	7.9	215	85	3.0	2.5	15.0	0.060	0.038	226	<4	<4	0.750	0.014	0.720	0.041	3.0	2.000	39.5	<4	<4	10.5
Sturtevant (u)	<4	<4	==	7.6	198	69	3.5	3.5	<4	0.120	0.074	205	<4	<4	0.570	0.017	0.585	0.164	<4	<4	51.0	<4	<4	5.5
Sturtevant (d)	0.02	0.34	==	7.7	220	89	2.5	3.5	15.0	0.125	0.087	72	<4	<4	0.475	0.018	0.490	0.085	3.0	0.200	44.0	<4	<4	9.0
Wilkins	<4	<4	==	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
Phantom	<4	<4	==	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4

Shaded data= >30% of reported observations less than detection limit, table value is median of concentrations above detection limit.
<4 = reported observations number less than 4.

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Appendix B: Parameter Yield Comparison

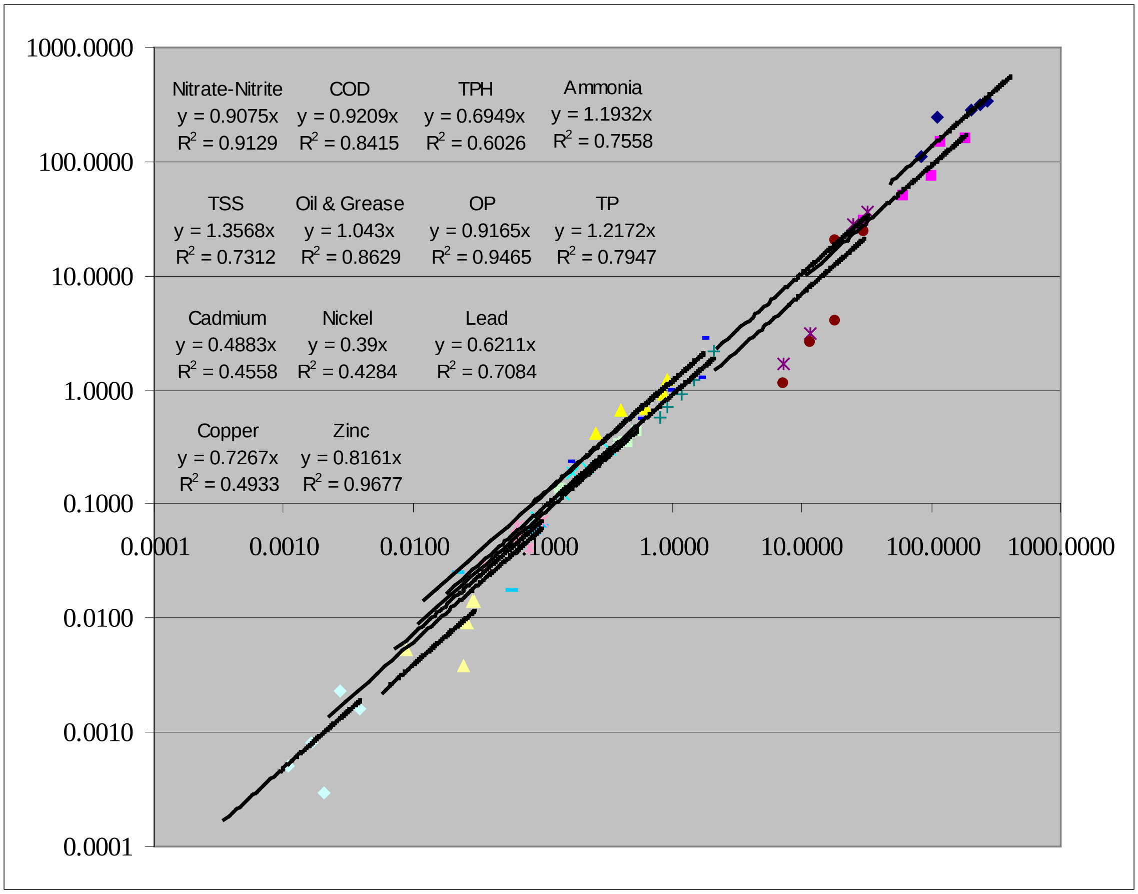

Figure B-1. Comparison between the pollutant yields estimates by this analysis (x-axis) and those reported in the Bellevue study (y-axis).

Appendix C: Box Plots of Storm-Event Parameter Levels

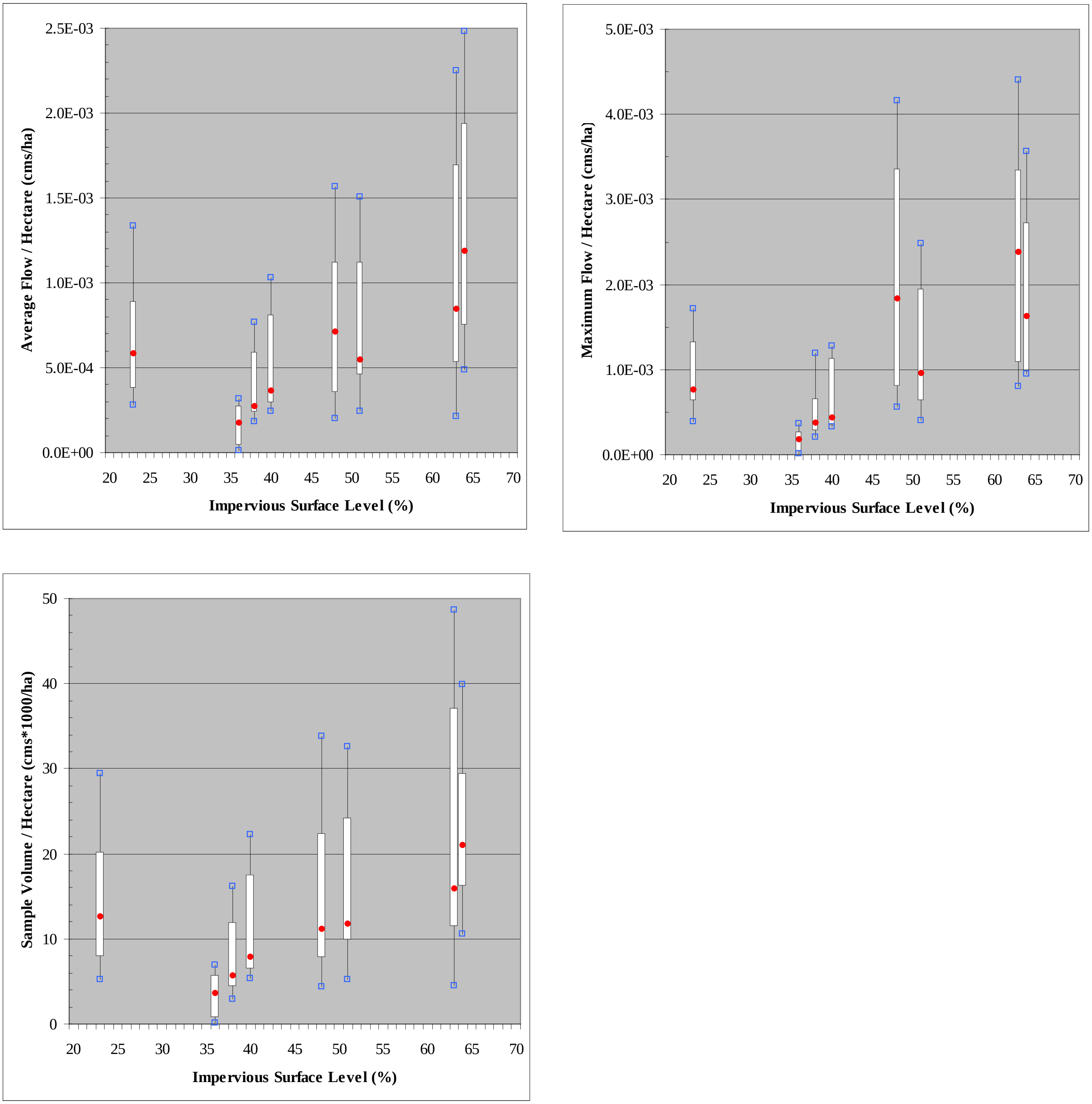

Figure C-1. Box plots of flow characteristics observed during storm event monitoring, by impervious surface level.

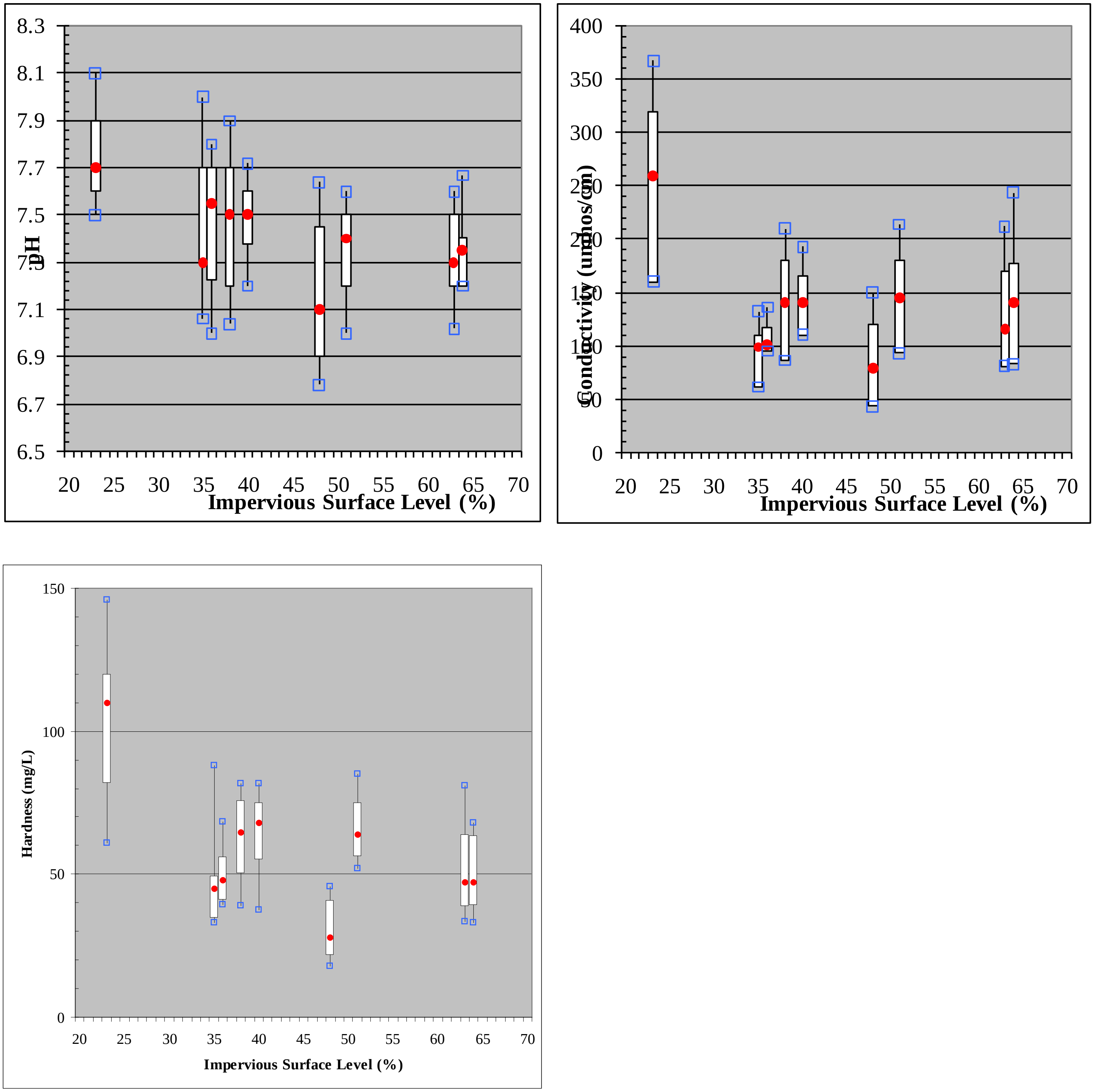

Figure C-2. Box plots of pH, conductivity, and hardness observed during storm event monitoring, by impervious surface level.

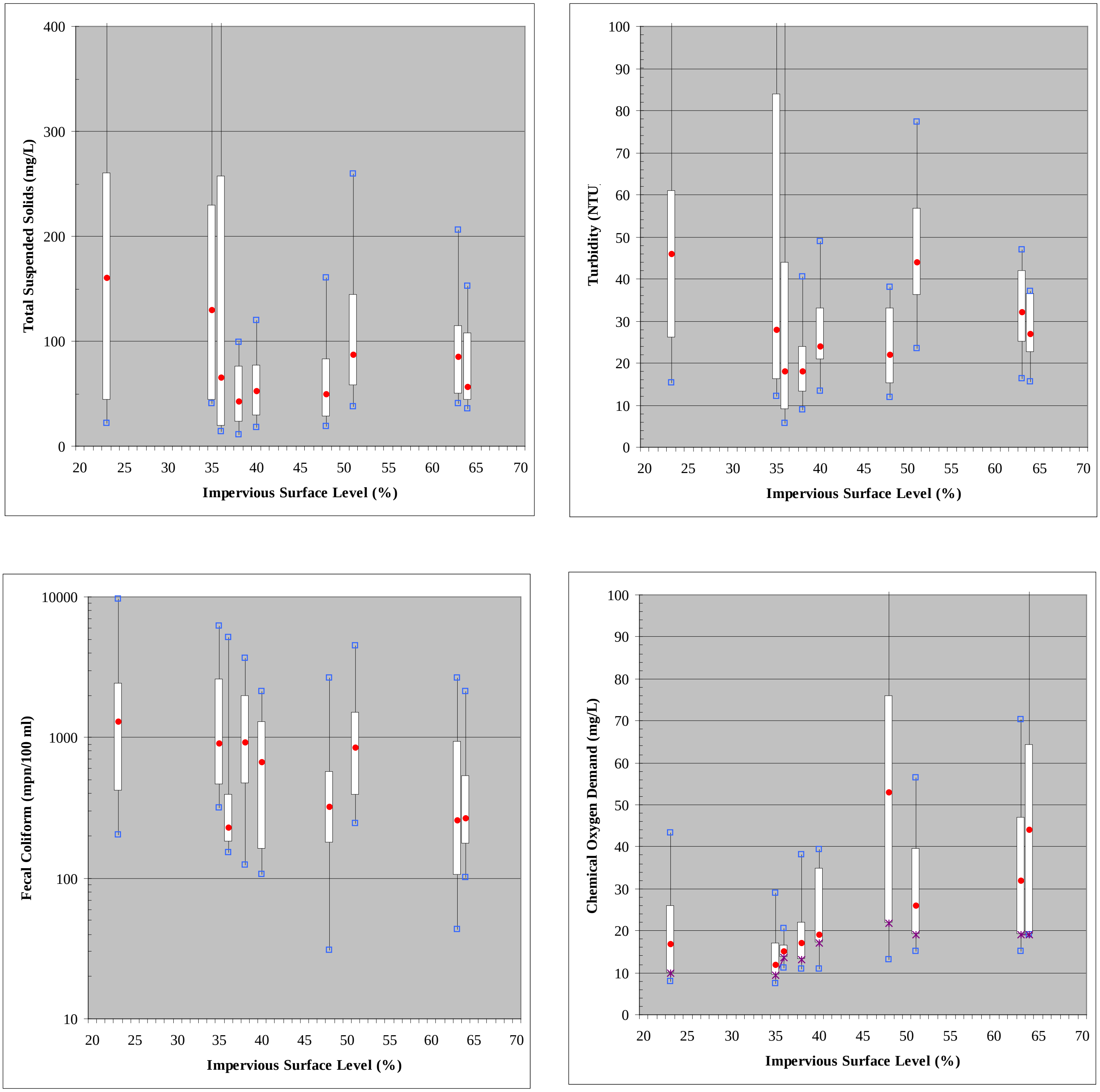

Figure C-3. Box plots of TSS, turbidity, fecal coliform, and COD levels observed during storm event monitoring, by impervious surface level.

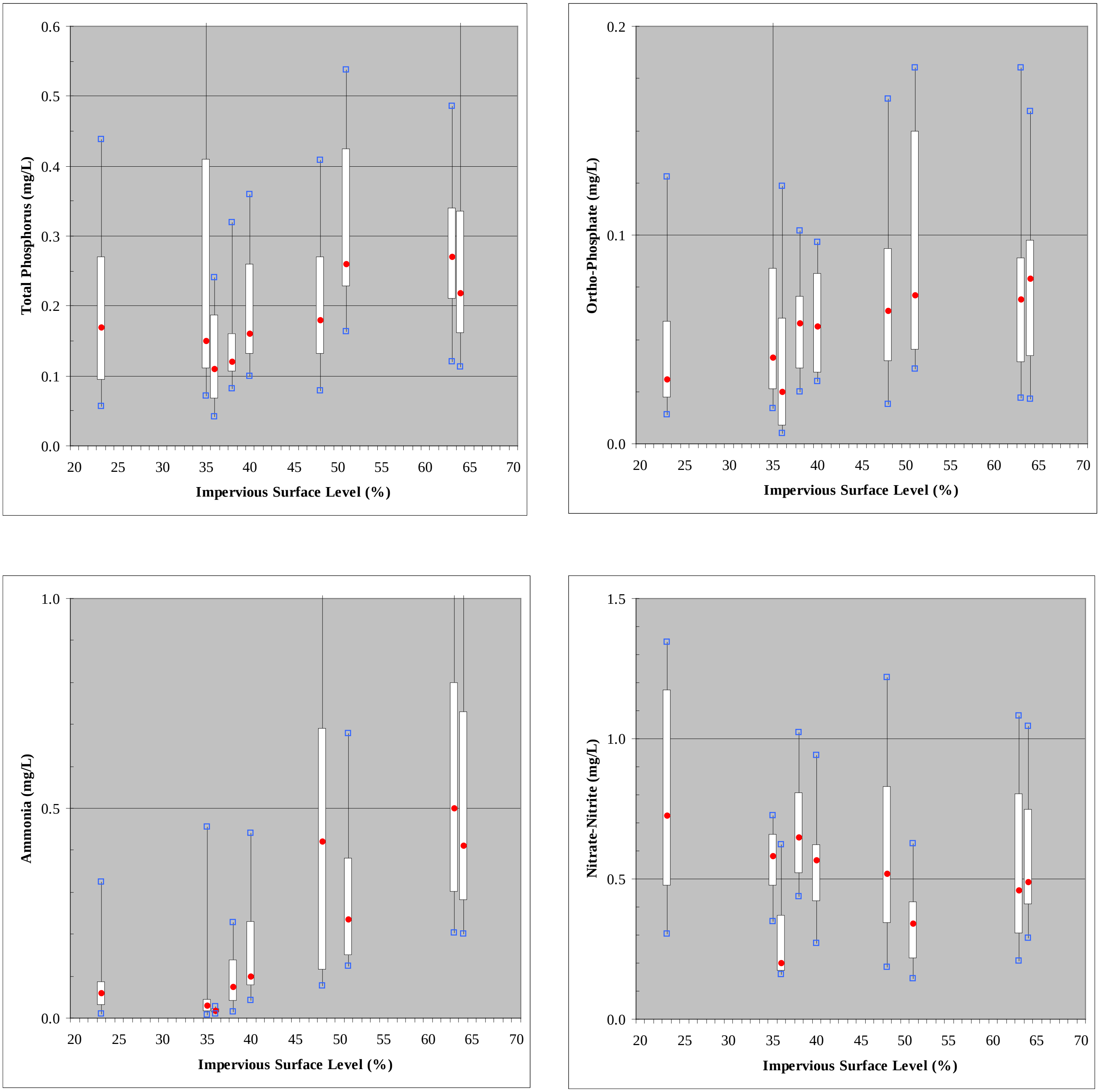

Figure C-4. Box plots of total phosphorus, ortho-phosphate, ammonia, and nitrate-nitrite levels observed during storm event monitoring by impervious surface level.

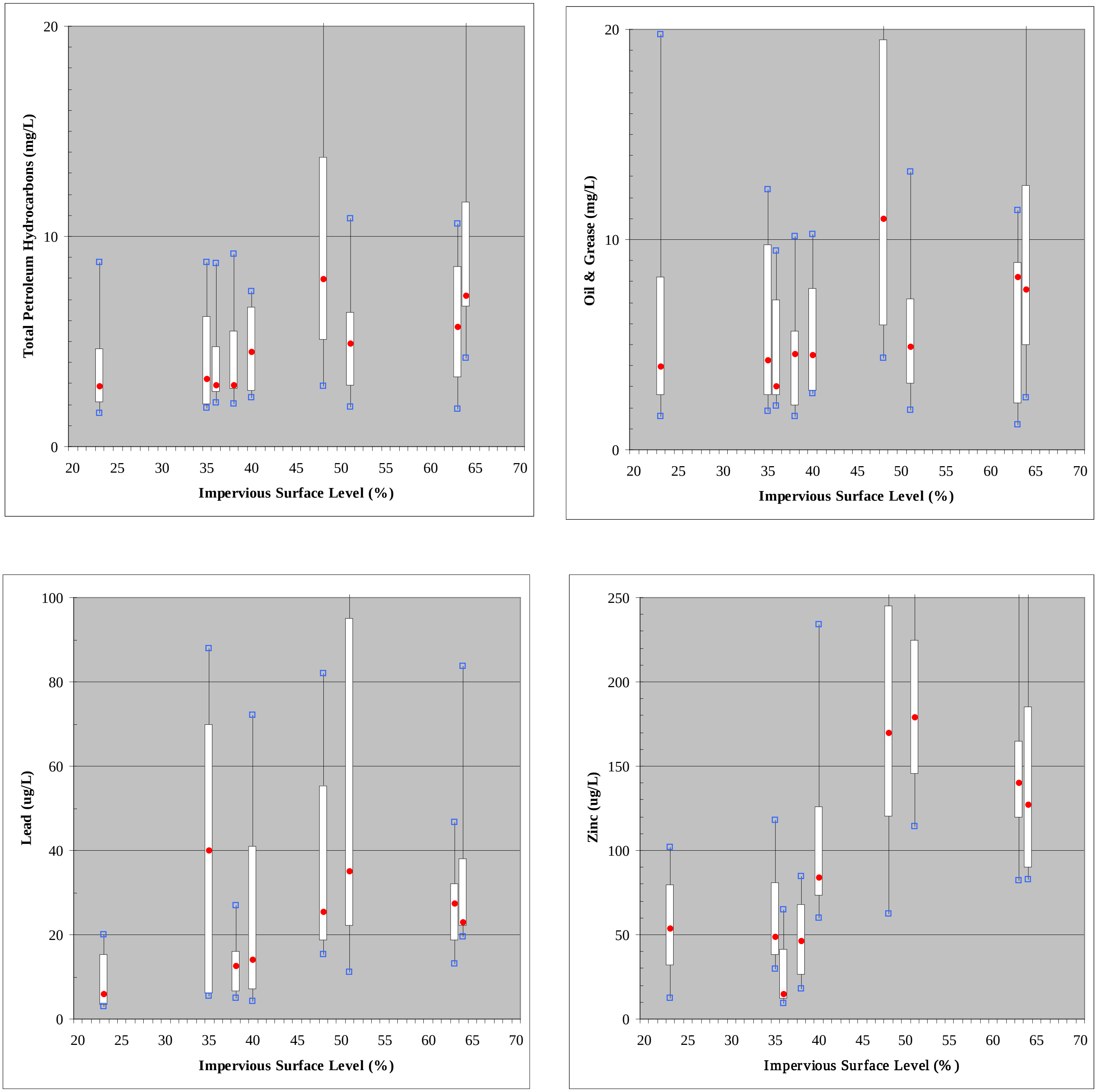

Figure C-5. Box plots of total petroleum hydrocarbons, oil and grease, lead, and zinc levels observed during storm event monitoring by impervious surface level.

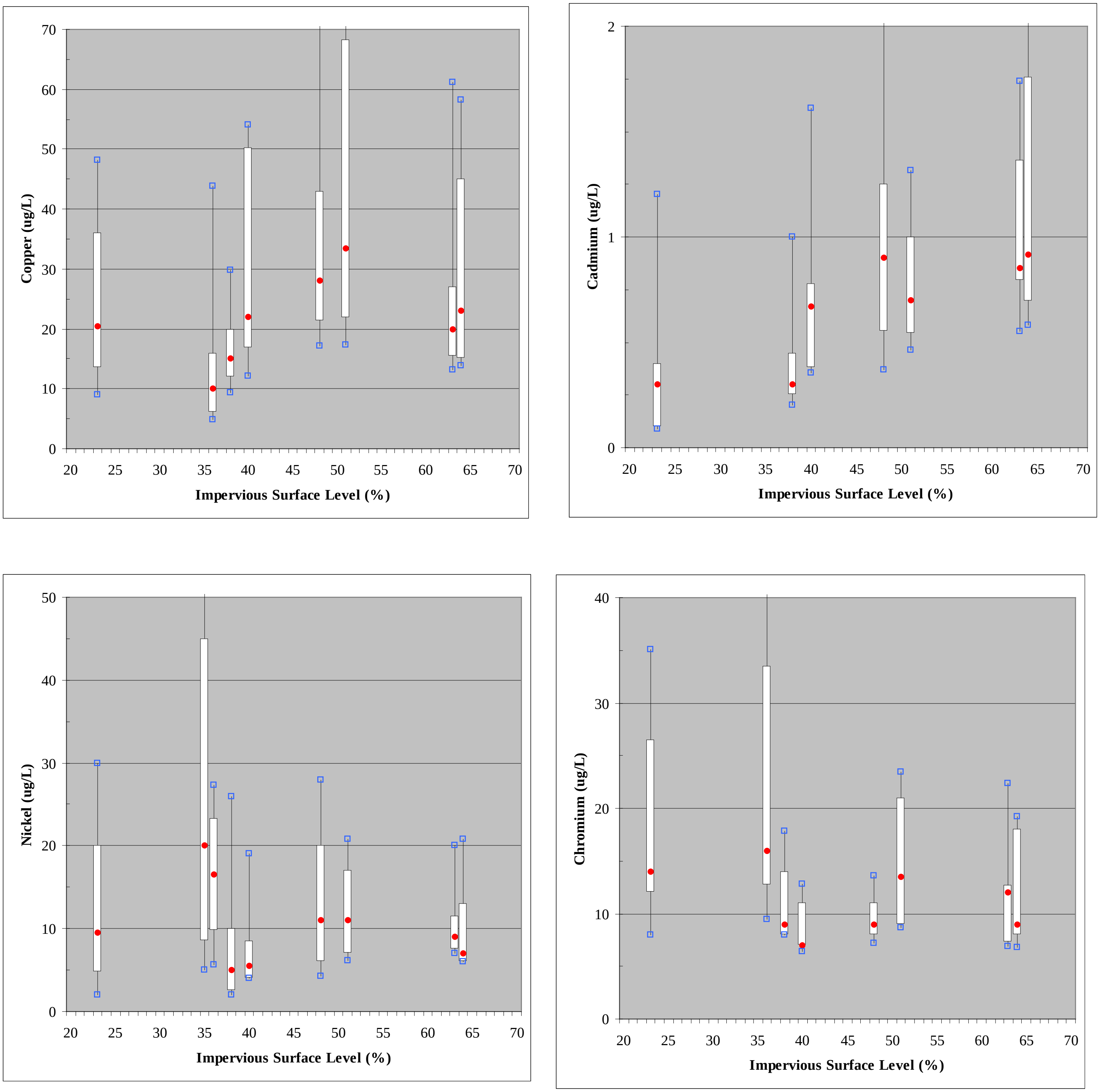

Figure C-6. Box plots of copper, cadmium, nickel, and chromium observed during storm event monitoring, by impervious surface level.