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Land Use, Impervious Surface, and Water Quality

City of Redmond

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Land Use, Impervious Surface, and Water Quality

City of Redmond

by

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Study Summary

The relationship between land use, impervious surface, and receiving water quality was examined within the city of Redmond, Washington. This study was initiated to provide Redmond's Natural Resources program with a better understanding of ways to reduce impacts to surface water quality from storm water runoff. Towards that end, a baseline understanding of the association between the city's various types of land uses, the generation of impervious surfaces, and therefore storm water runoff, was first required.

The city, with an area of 37 square kilometers, has 92 delineated storm water catchments ranging in size from about 1 to 291 hectares, with 15 of the catchments having long-term water quality monitoring data.

City-wide, the average impervious level is 34 percent, with levels ranging within the catchments from 1 to 77 percent. Sixty-five percent of the catchments, representing 74 percent of the city, have impervious surface levels above 20 percent, a level above which was found to result in chronic impairment of surface water quality. At build-out, a condition in which all current zoning is fully developed, 96 percent of the city will have average catchment impervious surface levels above 20 percent, with the average city-wide impervious surface level increasing to approximately 50 percent, a 47 percent increase from the current average. Based on current and estimated future impervious surface levels, Redmond is at an advanced stage of development, approximately 68 percent of the way toward a full build-out condition.

The largest increase in impervious surface, representing 42 percent of the future growth, will occur through further development of low/moderate density residential zoning. For this reason, implementing low impact development measures for this zoning designation provides the best opportunity for reducing future impervious surface growth. However, because the city is at an advanced stage of development, just managing the future growth in impervious surface will not provide a significant reduction in stormwater-related impacts to surface water quality on a city-wide basis. To better manage and treat current runoff, modification to the city's existing infrastructure that both directly reduces impervious surfaces during redevelopment opportunities, limiting stormwater generation, and providing increased storage and infiltration to more effectively manage and treat current runoff is required.

Though this study applies to Redmond in particular, it provides an analysis framework that can be initiated at various stages of land use planning. Much of it is based on commonly available geographic information systems data. Therefore, it can be relatively easily duplicated by cities and counties, providing a means to understand the relationship between current or potential land use decisions, the generation of impervious surface and, in turn, impacts to water quality.

A separate though complimentary report was also generated as part of this work titled: *'Review of Storm-Event Water Quality Data: City of Bellevue'*.

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Study Scope

This study was initiated to provide the city of Redmond's Public Works, Natural Resources program with a better understanding of ways to reduce impacts to surface water quality from stormwater runoff. To provide a foundation to these recommendations, a fuller understanding of the city's infrastructure associated with stormwater generation was first required. This report addresses this initial assessment through completion of the following analyses:

- Characterization of land use zoning and its distribution throughout Redmond.
- Calculation of impervious surface levels characteristic of specific types of zoning.
- Estimation of current and future impervious surface levels by stormwater catchment and land use zoning delineations.
- Identification of the relationship between impervious surface and water quality in perennial surface water drainage.

These various analyses provided the basis for examining the relationship between land use, impervious surface, and water quality within Redmond. This analysis was carried further through the estimation of impervious surface levels expected at full build-out, or a state where all types of zoning are fully developed, and its implications to future water quality.

Study Methods

Characterization of land use and impervious surface: current and future

Central to this analysis was the use of two 30-meter resolution grids of land use classifications and impervious surface levels created for the greater Puget Sound region (Sanborn, 2005). The grids were based on 2001 data. Both were sampled using the geographic information systems (GIS) software ArcGIS (V. 9.0) and its extension, Spatial Analyst.

The land use grid is categorized into the following: high, medium, and low density development, cultivated, grassland, forest, and wetlands.

The impervious surface grid values were continuous from 20 percent to 100 percent; levels below 20 percent were given a value of 0. The analysis results from the grid generate an assessment of *total* impervious surface as opposed to an *effective* impervious surface level. The difference is that effective only considers those surfaces directly contributing to surface runoff, while total impervious surface accounts for surfaces that may not directly contribute. An analysis of effective impervious surface levels within Redmond's storm water catchments was conducted in 2006 (NHC, 2006). Despite differences in the

impervious surface metric, the estimates are comparable (refer to Appendix B). In fact, the impervious surface levels determined for the catchments by this analysis are lower by about 16 percent in comparison to the estimated effective impervious surface levels. This is likely due to the lack of continuous grid values below 20 percent, resulting in a conservative estimate of total impervious surface. The use of total, as opposed to effective impervious surface is a more appropriate measure for this type of analysis, especially given the setting. This is because current standard construction practices, during the initial phases of new development, typically includes the removal of existing vegetation and surface organic soils layers at the site. While some vegetation may ultimately be restored to the site, depending on the type of development, this commonly resides over heavily compacted surface soil layers. Soil compaction, combined with an overlying grass vegetated surface, effectively functions hydraulically as only a semi-pervious surface. However, these types of surfaces may be regarded as pervious in the effective impervious surface measure, resulting in an underestimation of their total contribution to storm water runoff generation.

The relationship between 2001 impervious surface levels, representing the current condition within Redmond, and impervious surface levels associated with a future build-out condition, based on the city's current land use zoning designations, was determined using the following methods:

- Two GIS covers, one delineating stormwater catchments within Redmond and the other delineating various types of land use zoning, both generated by the city, were each clipped to the current (2007) city boundary and intersected. The resulting cover provided the delineation of each designated type of land use within each of the city's 92 stormwater catchments.
- From this new intersected cover, and using the ArcGIS extension Spatial Analyst, the average level of impervious surface for each of the defined land use designations, within each of the catchments, was determined. This analysis defined the current average impervious surface condition.
- These data were then analyzed collectively, on a city-wide basis, to determine representative impervious surface levels associated with each land use type. The dataset, consisting of 347 records of individual zoning designations and their associated impervious surface levels, were sorted by land use zoning type. The data were further sorted into 12 primary land use zone groups (refer to Table 1).

For each of the groups, the 90th percentile was calculated from the record of average impervious surface levels for polygons having an area greater than one hectare. It was assumed that the 90th percentile impervious surface level, specific to each land use group, represented its associated build-out level or the level expected at full development. This approach was used because not all of the land use designations within the city have been fully developed. For instance, areas within the city designated for low density residential development may currently exist as forest-land with minimal impervious surface.

- From this information, the average impervious surface level, expected at build-out, was estimated for each of the catchments. This calculation was based on the type and level of representation (area delineated) of the various land use groups within each of the catchments and their respective 90th percentile impervious surface levels. This calculation resulted in an estimation of the area-weighted average future impervious surface level, by catchment and extended city-wide.

Progression to build-out

In order to determine opportunities to reduce future impervious surface levels, an estimate of the current stage in the progression toward full build-out was necessary. This measure provides a basis for defining, by catchment and land use, the magnitude and location of the potential growth in impervious surface. This metric, referred to as the “build-level”, was estimated by both catchment and type of land use through the following method:

- The current percent build-level for each catchment was determined by dividing the current (2001) average impervious surface level by the estimated build-out impervious surface level and multiplying by 100.
- To determine the build-level by land use, the data were sorted into 12 primary land use groups (refer to Table 1). Each land use group contained the total record of individual delineations and their average impervious surface levels throughout the city. For each land use group, the current average impervious surface level was calculated by multiplying the area (as decimal) each polygon (data record) is represented within the city (defined for the particular land use group) by its respective current average impervious surface level. Again, by this method, the impervious surface levels are weighted based on their level of representation. The sum of these records was then taken to arrive at an overall area-weighted average impervious surface level representative of each land use group city-wide. The current percent build-level was then determined for each land use by dividing its current average impervious surface level by its characteristic 90th percentile impervious surface level and multiplying by 100.

Change in land use practices on future impervious surface levels

The effect of decreasing the 90th percentile impervious surface level (the level that characterizes the impervious surface associated with each type of land use zoning) on the ultimate built-out level, or future condition, was examined through the following method:

- The 90th percentile impervious surface level associated with each of the major land use groups, representing the build-out condition, was decreased sequentially by 10 percent to a maximum reduction of 50 percent.
- Each of these reductions was multiplied by the current un-built percent and the total area each land use group represents within the city. These estimates of future increases in impervious surface were then added to the current levels estimated for

each land use group. The relative effect of these impervious surface changes were evaluated sequentially by land use zone type, and accumulatively for all land uses, to assess their effect on a city-wide basis. (The results of these analyses are presented in Table 6.)

Characterization of surface water quality: water quality score

The city of Redmond has collected water quality data at 41 locations within the greater city since 1995. This analysis focused on 15 of these monitoring stations due to their larger data record and collection consistency. The water quality parameters collected include flow; temperature; dissolved oxygen; conductivity; pH; turbidity; total suspended solids; fecal coliform; total phosphorus; and total nitrogen. In many cases, the monitoring stations did not share exactly the same sampling dates or a similar sampling frequency. The sampling frequency for some of the stations occurred quarterly, and monthly for others. Because of the differing sampling periods among the stations, this analysis did not attempt to examine the water quality observed on a particular date or during a defined period. Instead, it focused on providing an overall characterization of water quality.

Water quality score

To compare the overall water quality among the stations a ranking system, or score, was developed. The water quality score provides a general index, based on an evaluation of several parameters. Once determined, the relationship between water quality scores and associated average catchment impervious surface levels, up-gradient of the monitoring location, were examined.

The score was used to identify chronic water quality impairment, since sampling was structured on routine monitoring as opposed to targeting storm events. It is assumed that monitoring locations that display chronic water quality impairment also experience stormwater runoff-related impacts. The link is made through the association of chronic water quality impairment and impervious surface levels.

From each monitoring station's dataset the minimum, median, and maximum were determined for each of the water quality parameters measured. The water quality data used in the ranking included maximum water temperature; minimum dissolved oxygen; maximum pH; median turbidity; median fecal coliform; median total phosphorus; and median total nitrogen levels. These parameters were chosen because they were collected consistently. From these indices, a water quality score was determined through the following methods:

- To generate the ranking statistic for each parameter, the data (by monitoring location) were ranked from lowest to highest and the overall median value determined. The median parameter level was then assigned a value of 0. For instance, in the case of temperature, maximum temperatures were ranked from lowest to highest. Maximum temperatures ranged from 14.2°C to 23.0°C. The overall median maximum temperature among the stations was 18.0°C. Stations

with a median of 18°C were assigned a value of 0. Stations with maximum temperatures below 18°C were sequentially assigned decreasing scores (-1, -2...) while stations with temperatures above 18°C were assigned increasing scores (1, 2, ...). (Lower scores indicate better water quality characteristics.)

- Parameters below the median were given negative rankings for maximum temperature, maximum pH, median turbidity, median fecal coliform, median total phosphorus, and median total nitrogen. Minimum dissolved oxygen levels below the group median were assigned positive scores, indicating lower water quality. Once the ranking of each parameter was complete, an overall sum, the water quality score, was determined for each station. (Appendix C includes an overview of the monitoring stations used in the evaluation, the water quality data, its ranking by parameter, and the overall water quality score. Box plots of the water quality data for the 15 primary monitoring stations used in this analysis in addition to others within Redmond are also included.)

Results and Discussion

Current land use and impervious surface levels

Land use

The city of Redmond, encompassing an area of about 37 square kilometers, is situated in the Puget Sound lowlands approximately 17 kilometers east of Seattle. The city has an average elevation of 56 meters with low relief; elevations range from 7 meters where the Sammamish River intersects the city boundary to 107 meters in the southwestern Overlake section. Lake Sammamish is situated just south of the city and Lake Washington 7 kilometers to the east. Connecting the two lakes is the Sammamish River, which bisects Redmond as it flows north to Lake Washington. The river is a major hydraulic feature of the city and importantly, in terms of this analysis, most of the surface water drainage from Redmond is ultimately directed to it.

In 1963, the Evergreen Point Floating Bridge (Highway 520) was completed, spanning Lake Washington and connecting Seattle to the east side of Lake Washington. This transportation access and the availability of relatively inexpensive, undeveloped land led to major land use changes. Since the completion of the bridge, Redmond changed from a largely agricultural community to a highly developed residential and commercial landscape. The city population, as of 2003, was approximately 46,000.

A generalized description of land use within Redmond is presented in Figure 1. This description is broken down into three relative levels of development, based in their ranges in associated impervious surface and so includes everything from highways to residential development. The development intensity levels are a reflection of impervious surface levels. Other land use descriptors include forest and wetland covers and farmland.

As observed from Figures 1 and 2, low- and medium-density development represents the largest general land use types in Redmond, comprising approximately 30 percent and 23 percent of the city, respectively. Low-density development has an associated impervious surface level of between 20 and 49 percent, while the impervious surface level associated with medium-density development is between 50 and 79 percent. High-density development, representing 10 percent of the city, has an associated impervious surface level of between 80 to 100 percent. High- and medium-density development is concentrated within the city center, continuing north through the Sammamish valley and along the Highway 520 corridor through the southeast Overlake section of the city, adjacent to the city of Bellevue. Low-density development is more dispersed throughout the city, intermingled with medium-density development levels.

Based on these development levels, their representation within the city, and their average associated impervious surface level, the approximate average city-wide impervious surface level is 34 percent.

Forest cover, while representing 16 percent of the city, is largely confined to land with steep slopes where construction potential is marginal and likely restricted (Figure 1). A vestige of farmland, once central to the Sammamish River valley, is now only situated in the most northern portion of the valley that lies within the city. Wetland systems are most represented within the Sammamish River valley as well as lower Bear Creek. The bare land use description present in Figure 1 is referenced to a gravel pit situated in the southeastern portion of the city in the lower Bear-Evans Creek drainage.

There are 92 storm water catchments delineated within Redmond (refer to Figure 9). Considering the land use represented within a subset of these catchments, it is apparent that the level of high and medium development present is highly correlated to the average level of impervious surface (Figure 3). High and medium development-type land uses are associated with up to a 90 percent+ impervious surface level. As expected, increases in impervious surface levels, associated with development, result in the decline of vegetative cover (forest and grasslands) (Figure 4).

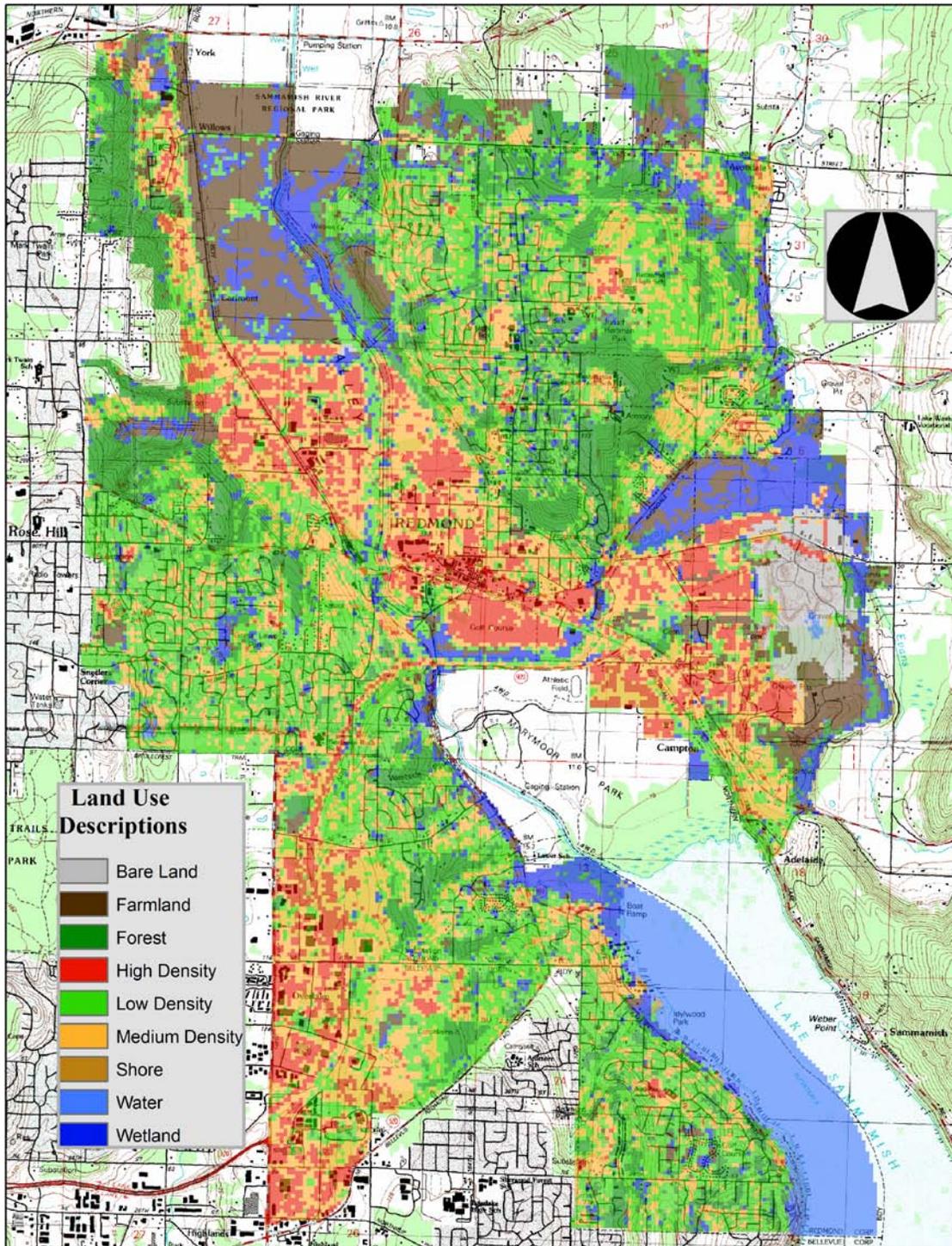


Figure 1. The representation and distribution of several generalized descriptions of land use within the city of Redmond.

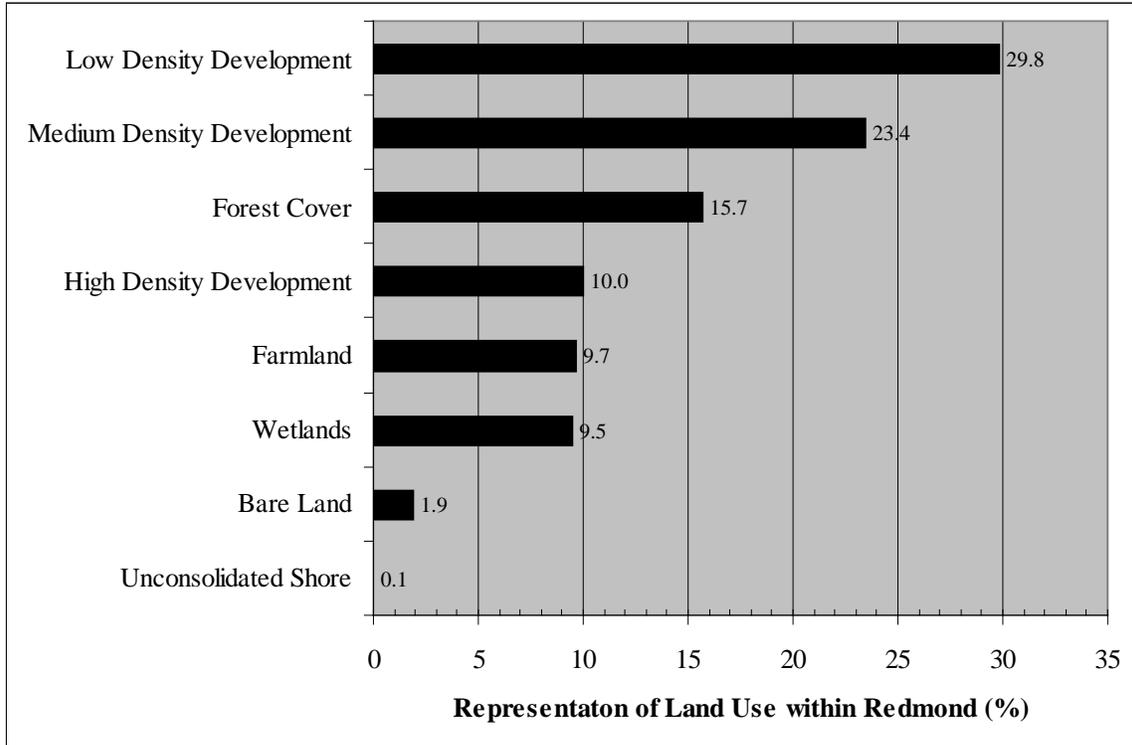


Figure 2. The representation of various land uses within Redmond (2001).

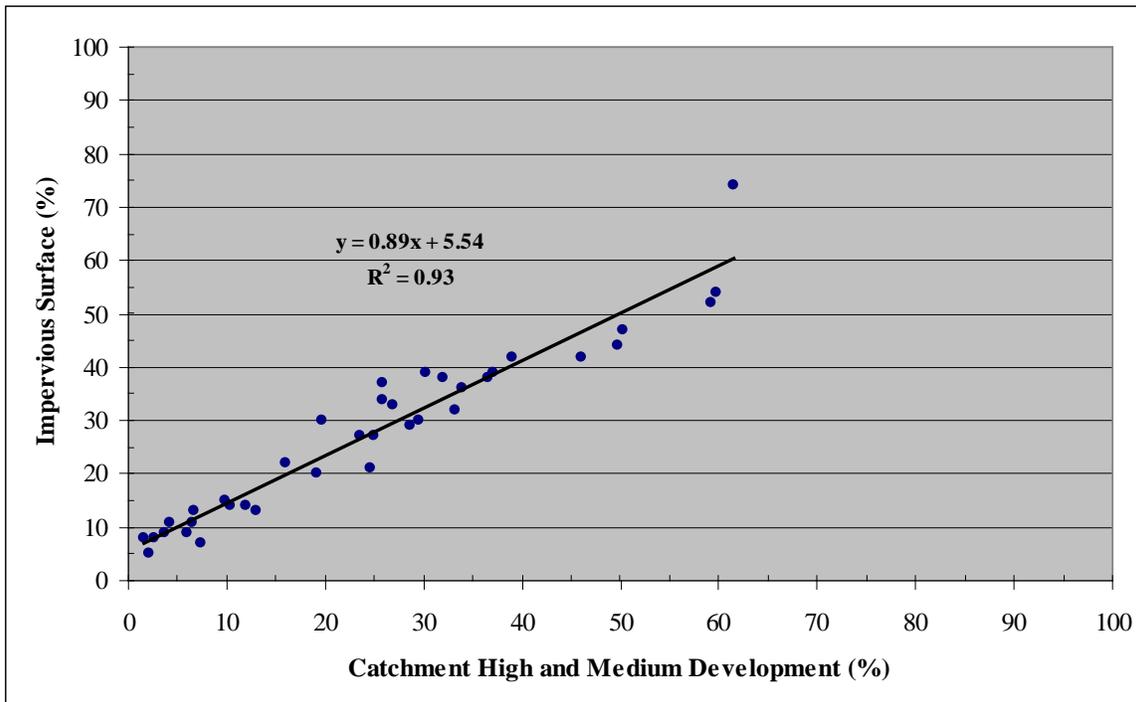


Figure 3. Association between high and medium density development and average impervious surface observed within storm water catchments.

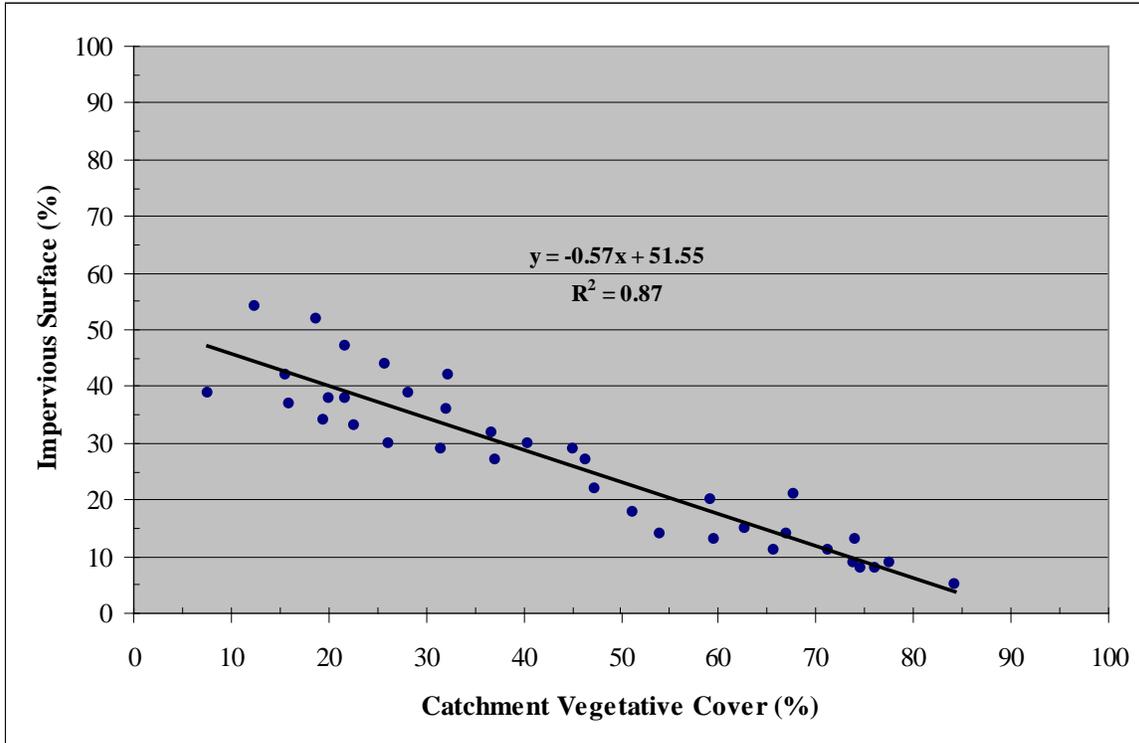


Figure 4. Association between level of vegetative cover (forest and grassland) and average impervious surface within storm water catchments.

Future land use and impervious surface levels

An indication of potential transformations to Redmond’s landscape, associated with future development, can be estimated by considering the city’s current land use zoning. While the city has specified about 36 different zoning designations, for this analysis zoning sharing similar development characteristics were grouped together to form 12 general zoning categories (Figure 5).

As a percent of the total city area, low-to-moderate density residential development is the most highly represented, at about 45 percent. Overlake mixed use and manufacturing park each represent about 9 percent of the city, with high- and moderate-density residential development representing 5 and 7 percent of the city, respectively (Figure 6). Land use associated with higher impervious surface levels, city center and business park type zoning, each represent about 6 percent. This is balanced by zoning with lower impervious surface levels, like large-lot residential and parks.

Impervious surface levels characteristic of each of these land use zoning types are presented in Figure 7. Overall, the levels tend to be lower compared to those presented in the general land use descriptions presented previously, due to the sampling method used. However, the city’s zoning groups can be divided into similar generalized development categories. For instance, the Overlake mixed use, manufacturing park and city center could be considered high-density type development. The impervious surface level associated with these zones ranges between 72 to 81 percent. Large lot residential and

low/moderate density residential could be classified in the low-density development category. Impervious surface levels associated with these land uses range between 19 and 43 percent. The other zone types fall into the medium-density development category, with associated impervious surface levels falling between 53 and 63 percent. Therefore, based on these groupings; assuming that this zoning scheme represents an expected future condition; and considering the total area they represent within the city and the mid-range of each group's associated impervious surface level, at full build-out the average impervious surface level city-wide would increase to about 45 percent, a 32 percent increase from the estimated current level. (This estimate will again be calculated in this report though applying different methods.)

Though not applied in this analysis, impervious surface levels, characteristic of each land use group, were also examined through a cumulative frequency type of analysis (based on 30 m² estimates) and through box plots (based on land use delineations city-wide). The results of these analyses are presented graphically and included in Appendix A.

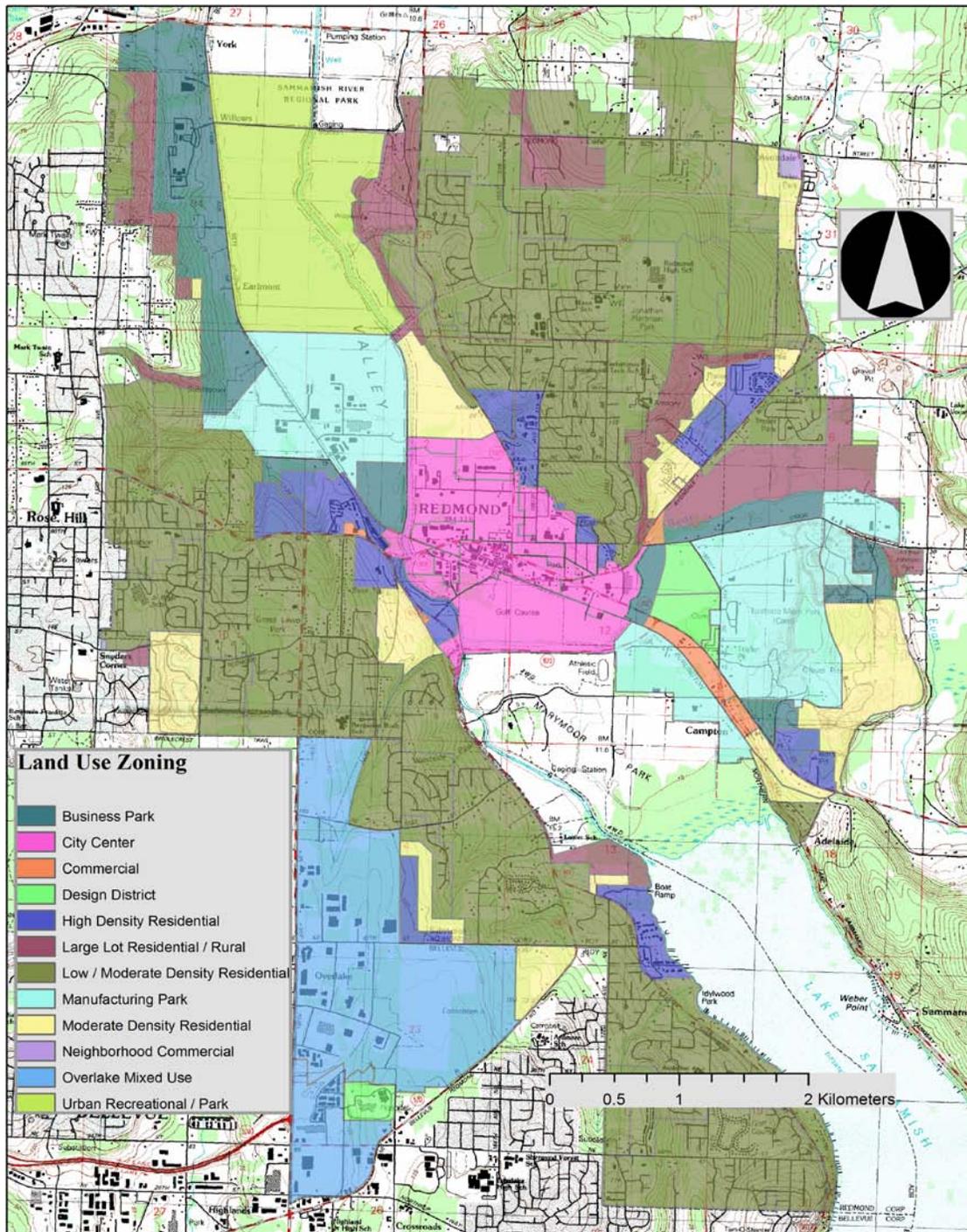


Figure 5. The representation and distribution of land use zoning within Redmond.

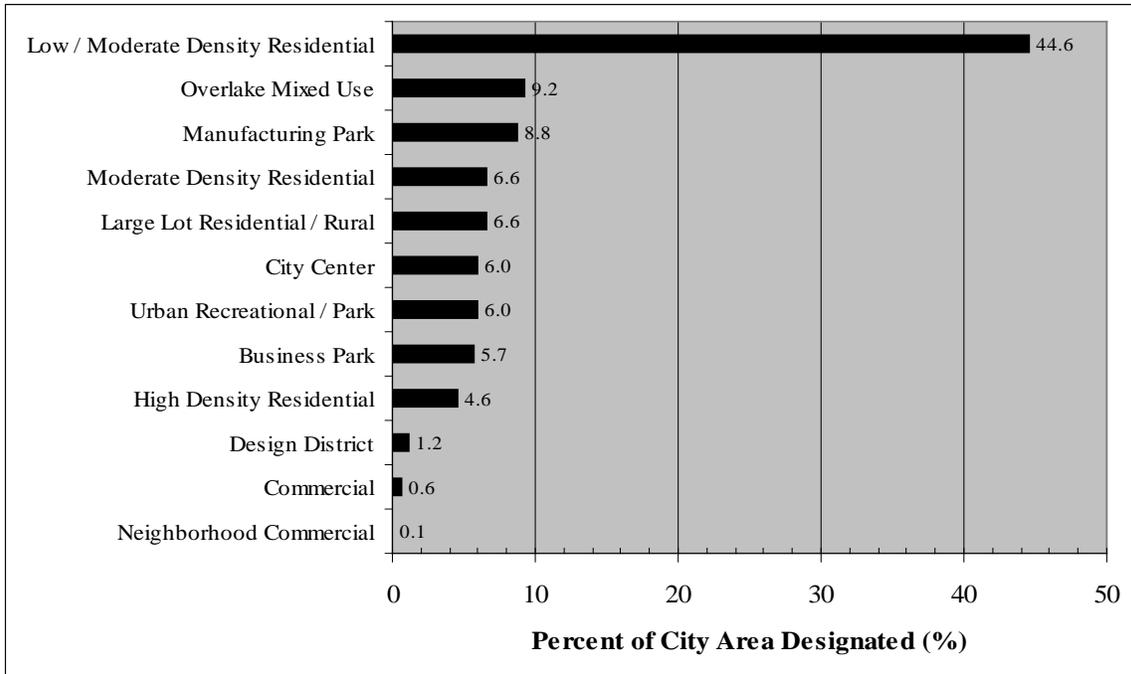


Figure 6. Percent of the city designated to various types of land use zoning.

Figures 8 and 9 display the current and projected estimates of impervious surface within Redmond’s stormwater catchments. On a city-wide basis, this information is summarized in Figure 10.

The future condition is based on the current delineation of the city’s land use zoning at full build-out, or a condition of full development. As observed, at the build-out condition the city landscape will shift from a high representation of the lowest to the highest ranges of impervious surface.

Currently, the most highly represented level of impervious surface is the 30 to 40 percent range, representing about 28 percent of the city. The overall city average is 34 percent. Levels below 30 percent currently represent about 43 percent of the city, but will fall to 7 percent at build-out. The balance comes through the increased representation of impervious surface for the upper ranges. For instance, impervious surface levels at 50 percent and above currently represent about 17 percent of the city, but will increase to 52 percent at the build-out condition.

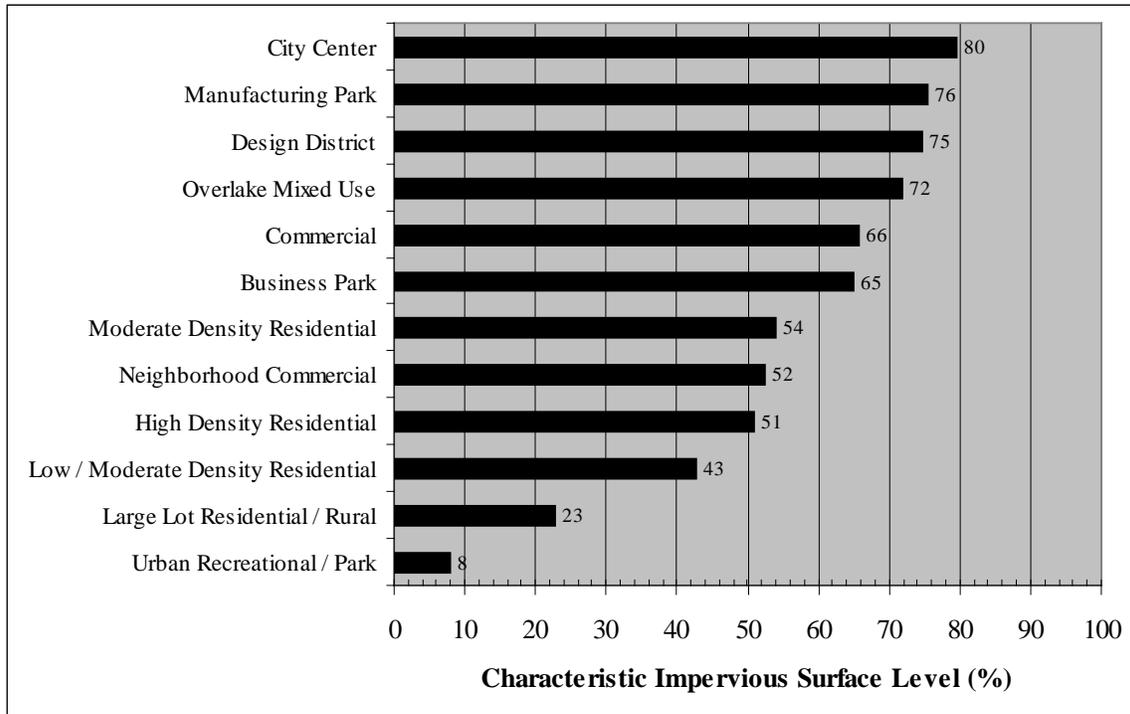


Figure 7. The impervious surface level characteristic of each type of land use.

Another way to assess this land use zoning information is to consider how far along Redmond is toward a full build-out condition. To determine this, a method was used which compared, by zoning delineation, current impervious surface levels to those expected at full development. The result is a metric known as the build-level. For example, assuming a current build level of 90 percent was estimated for a particular land use zoning type, there would only be a 10 percent expansion expected to achieve the build-out condition. It is calculated by dividing the current average impervious surface by the level expected at build-out, expressed as a percent. The underlying assumption is that each land use has a characteristic impervious surface level associated with it. If that level has not been uniformly achieved throughout its delineated areas within the city, then the build-out condition has not yet been achieved. Therefore, the level of current impervious surface is used as a surrogate measure of the development level.

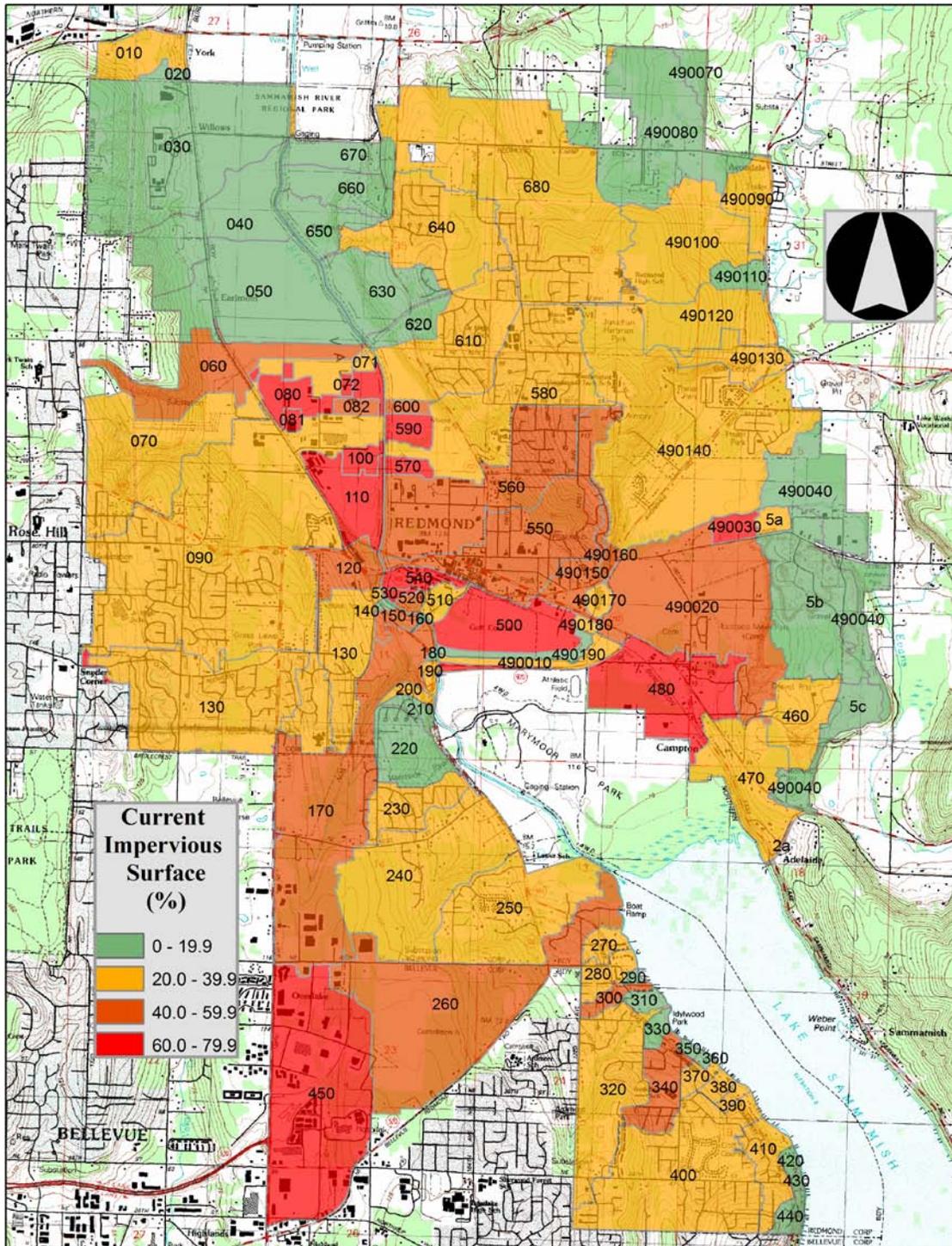


Figure 8. Current range in the average impervious surface level within stormwater catchments (numbered).

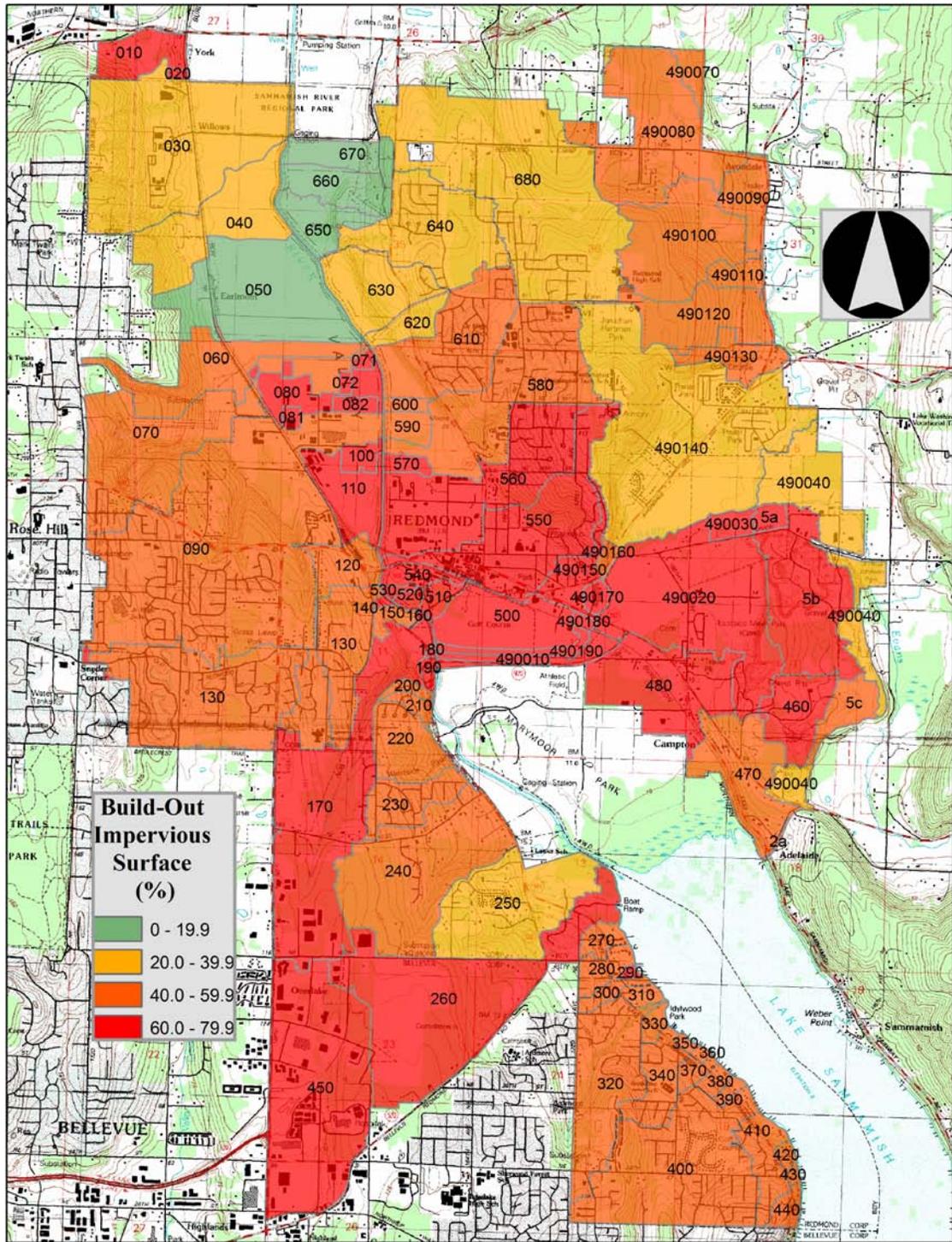


Figure 9. Future estimated range in the average impervious surface level within storm water catchments (numbered) at build-out.

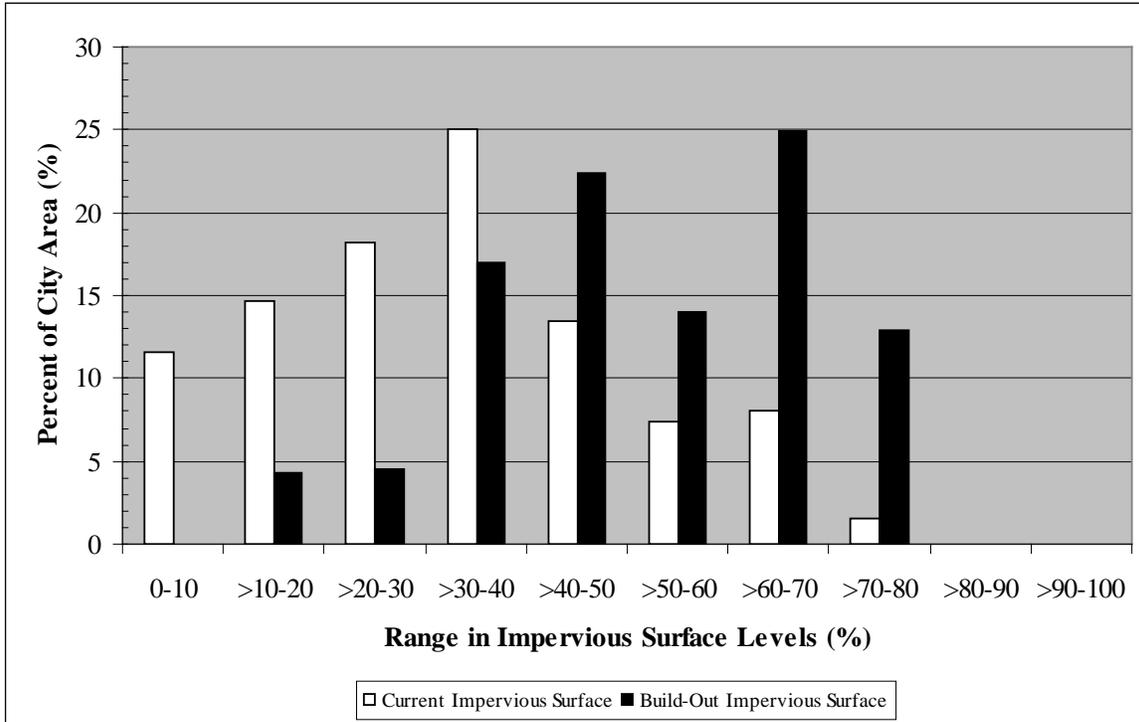


Figure 10. The area of the city represented by various ranges in impervious surface for the current (2001) and estimated build-out conditions (based on catchment averages).

Figure 11 presents ranges in estimated build levels for Redmond’s 92 stormwater catchments. Overall, the city has an average build level of 68 percent, indicating a further 32 percent expansion is possible. The majority of that will occur at the outer margins of the current city boundary where build-levels are lower. Evident from Figure 11 is that Redmond is at an advanced stage of development, with a high proportion of the city having build levels above 60 percent. This advancement is further indicated in Figure 12, where the representation of build levels for the highest ranges are disproportionately represented, or skewed, in relation to that of the lower ranges. Approximately 45 percent of the city is at a build level above 70 percent.

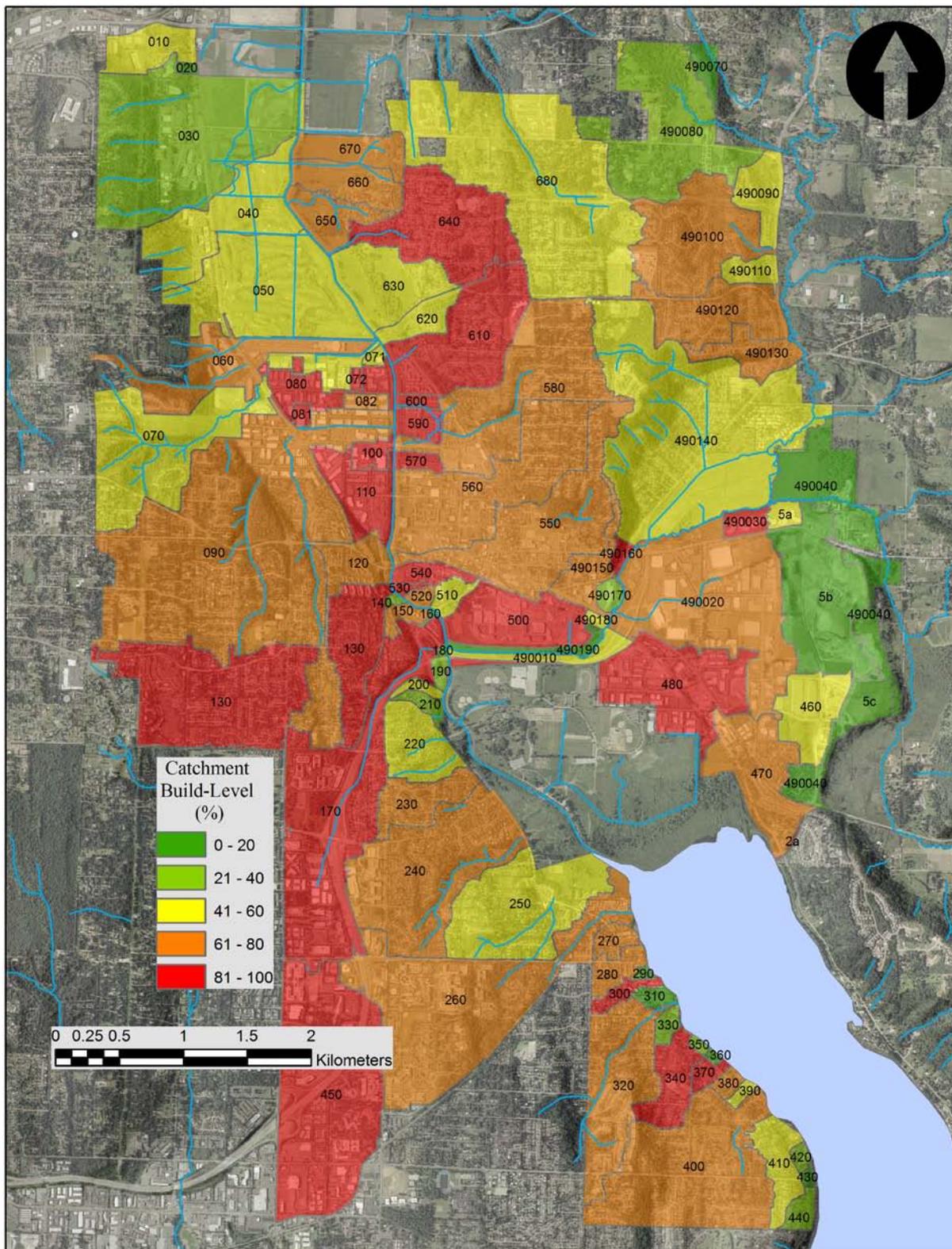


Figure 11. Current build-levels estimated for storm water catchments.

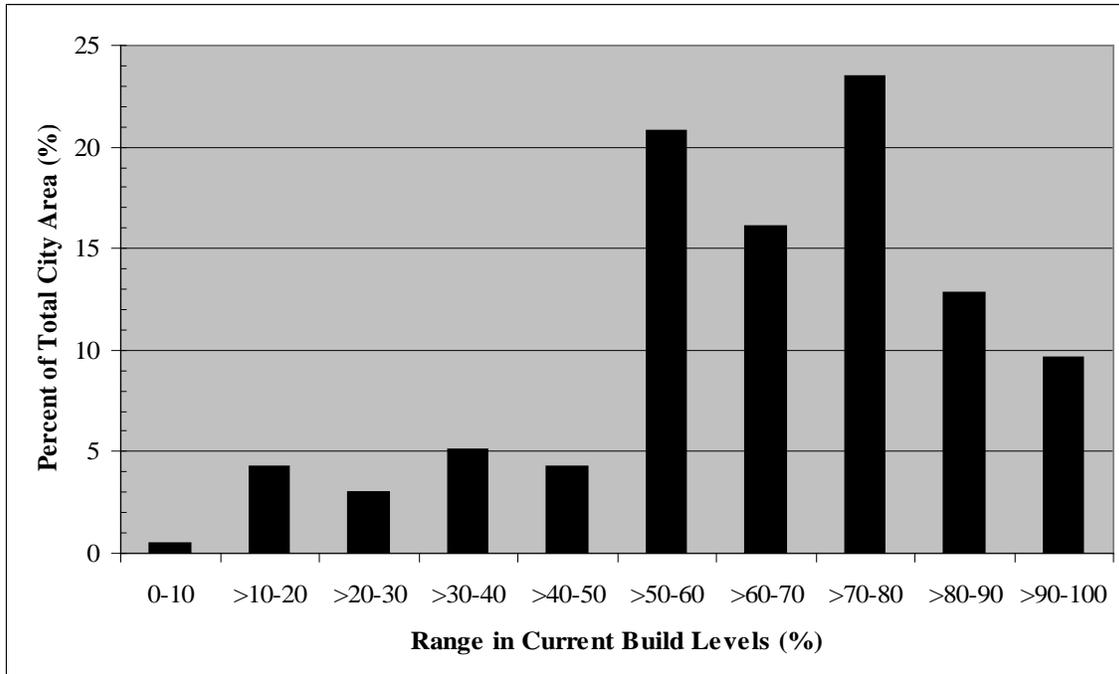


Figure 12. The area of the city represented by various ranges in build level (based on storm water catchment averages).

This analysis is carried further by examining the build levels for each zoning group. Table 1 provides a summary of this analysis, along with the area each zoning designation represents within the city, and the impervious surface level expected at build-out.

Redmond is primarily a residentially-developed city. Land zoned for residential development (high, moderate, low densities) occupies 63 percent of the city, while that zoned for commercial/industrial development occupies 32 percent. In particular, residential zoning levels at the low/moderate level (R3-6) encompass 45 percent of the city. It also has a relatively high associated 90th percentile impervious surface level at 43 percent. Moderate and high density type residential development has estimated impervious surface levels of about 50 percent, though they have a lower combined representation within the city at 11 percent. As shown in Table 1, zones commercial (84 percent), neighborhood commercial (96 percent), and Overlake mixed-use (86 percent) are currently at high build levels, indicating that they are close to a fully-developed condition. In addition, higher build levels are associated with city center (77 percent), high density residential (73 percent), design district (68 percent), and manufacturing-park type zoning (71 percent).

On an area-weighted basis, the current city average impervious surface level is 34 percent, though it is estimated, at build-out, to reach 50 percent, a 47 percent increase. The relative contribution to these city-wide totals, by type of land use, is presented in Table 1 in the columns titled current and future relative contributions to total impervious surface. The last column provides the percent contribution to future impervious surface by zoning type.

In evaluating these numbers, land use zone types at lower build-levels provide greater opportunities for implementing measures to reduce future growth in impervious surface levels than zones at current high build-levels. (It is less expensive to implement measures to control storm water generation during the construction phase rather than as a retrofit.) Currently, low/moderate density residential development contributes 12.3 percent to the current 34 percent impervious surface level observed city-wide. This represents about 36 percent of the total. At the build-out condition, it is estimated that low/moderate density residential development will contribute about 19.2 percent to the 50.3 percent total, representing about 38 percent of the total.

Another way to look at implementation opportunities is to examine the percent of the total future impervious surface attributed to each zone (Table 1, column “Percent Contribution to Future Impervious Surface”), assuming a build-out condition is achieved. For instance, manufacturing-park type zoning (MP, I) represents about 9 percent of the city, has a current build-level of 71 percent, and an associated impervious surface level of 76 percent. These characteristics result in it potentially contributing about 12 percent to future increases in impervious surface levels should it be fully developed. In comparison, city center (CC1-6), while having a high associated impervious surface level of 80 percent and representing 6 percent of the city, contributes about 7 percent to future impervious surface levels due to its current high build-level (77 percent).

In terms of commercial/industrial development, opportunities to reduce future impervious surface levels exist for the manufacturing-park (MP, I), moderate density residential (R8, R12, R18), and business park (BP) zone designations. However, the most significant opportunities to minimize future impervious surface levels are associated with low/moderate density type residential development (R3-6). Assuming full development, it will contribute about 43 percent of the estimated total increase in future impervious surface levels. While low/moderate density residential zoning has a relatively high build level (64 percent), it occupies a substantial portion of the city (45 percent), resulting in its potential of contributing 43 percent to the future growth in impervious surface levels (Figure 13).

Note on Using Table 1 – applying Business Park (BP) zoning

Each type of land use zoning has a characteristic impervious surface level. At a build-out, or a fully developed state, it is assumed that each of these respective impervious surface levels would be uniformly represented throughout the city. For instance, the impervious surface level associated with business park type zoning is 65 percent. If this zoning were fully developed, then wherever business park zoning is delineated throughout the city, impervious surface would be found uniformly at 65 percent.

The area column is the percent of the total city area represented by each land use group. Redmond’s current (2007) boundary encompasses an area of 37.2 square kilometers. Business park zoning is delineated within 5.57 percent or 2.1 km² of the current city boundary.

The **current build-level** is an estimate of the progression of development, by zoning designation, toward the full build-out condition. For instance, business park zoning has a current build level of 62 percent. This means that based on the level of impervious surface expected at full build-out (65 percent), in relation to the current average level throughout the city, a further 38 percent expansion can occur before the business park zoning is fully developed throughout Redmond.

Table 1. Land use zoning, its representation and associated impervious surface levels (current and future) within the city along with their relative contribution to current and future impervious surface levels.

Zone Description (Zone Symbol)	Build-Out Percentile Impervious Surface Level (%)	City Area ¹ By Zone (% of Total)	Current Build Level (%)	Current Relative Contribution to Total Impervious Surface (% of Total)	Future Relative Contribution to Total Impervious Surface (% of Total)	Percent Contribution to Future Impervious Surface (% of Total)
Neighborhood Commercial (NC)	52	0.12	96	0.06 (0.2%)	0.06 (0.1%)	0.02
Commercial (GC)	66	0.58	84	0.32 (1.0%)	0.38 (0.8%)	0.38
Design District (DD, GDD)	75	1.16	68	0.59 (1.7%)	0.87 (1.7%)	1.71
High Density Residential (R20, R30)	51	4.61	73	1.72 (5.1%)	2.35 (4.7%)	3.90
Business Park (BP)	65	5.75	62	2.32 (6.8%)	3.74 (7.4%)	8.72
City Center (CC1-6)	80	6.01	77	3.70 (10.9%)	4.81 (9.6%)	6.79
Urban Recreation/Park (UR, A)	8	5.97	39	0.19 (0.6%)	0.48 (1.0%)	1.79
Moderate Density Residential (R8, R12, R18)	54	6.61	54	1.93 (5.7%)	3.57 (7.1%)	10.08
Manufacturing Park (MP, I)	76	8.78	71	4.74 (14.0%)	6.67 (13.3%)	11.88
Overlake Mixed Use (OV, RC)	72	9.18	86	5.68 (16.7%)	6.61 (13.2%)	5.68
Lg. Lot Residential / Rural (R1, RA5)	23	6.58	29	0.44 (1.3%)	1.51 (3.0%)	6.60
Low/Moderate Density Residential (R3, R4, R5, R6)	43	44.66	64	12.29 (36.2%)	19.20 (38.2%)	42.45
Total	==	100%	==	33.97%	50.26%	100%

1) City area is 37.2 km²

A weighted-average impervious surface level for the city was determined for the current and build-out conditions. The current impervious surface average was determined, for each type of land use zoning, by multiplying its associated impervious surface level by the area the zoning represents in the city and by the current build-level. For instance, for business park zoning the associated impervious surface level is 65 percent, its total delineation represents 5.57 percent of the total city or 0.0557, and its current build-level is 62 percent or 0.62. Business park zoning, therefore, has a relative contribution of 2.3 percent to the city-wide average impervious surface level ($65 \times 0.0557 \times 0.62 = 2.3$ percent). The addition of all 12 zoning groups represented in Table 1 results in a city weighted-average sum of 33.97 percent. This is the current (2001) estimated city-wide average impervious surface level.

In a similar way, an estimate of the weighted-average impervious surface level expected at build-out can be calculated. This is achieved by multiplying the impervious surface level, associated with each zoning type, by its designated city area. This calculation assumes the build-level is 100 percent. The relative contribution to the city's total impervious surface level attributed to business park zoning expected at build-out is 65×0.0575 or 3.74 percent. The sum for all 12 groups results in an estimated future impervious surface level of 50.26 percent. From the current average city impervious surface level, a 47 percent increase is estimated once build-out is achieved.

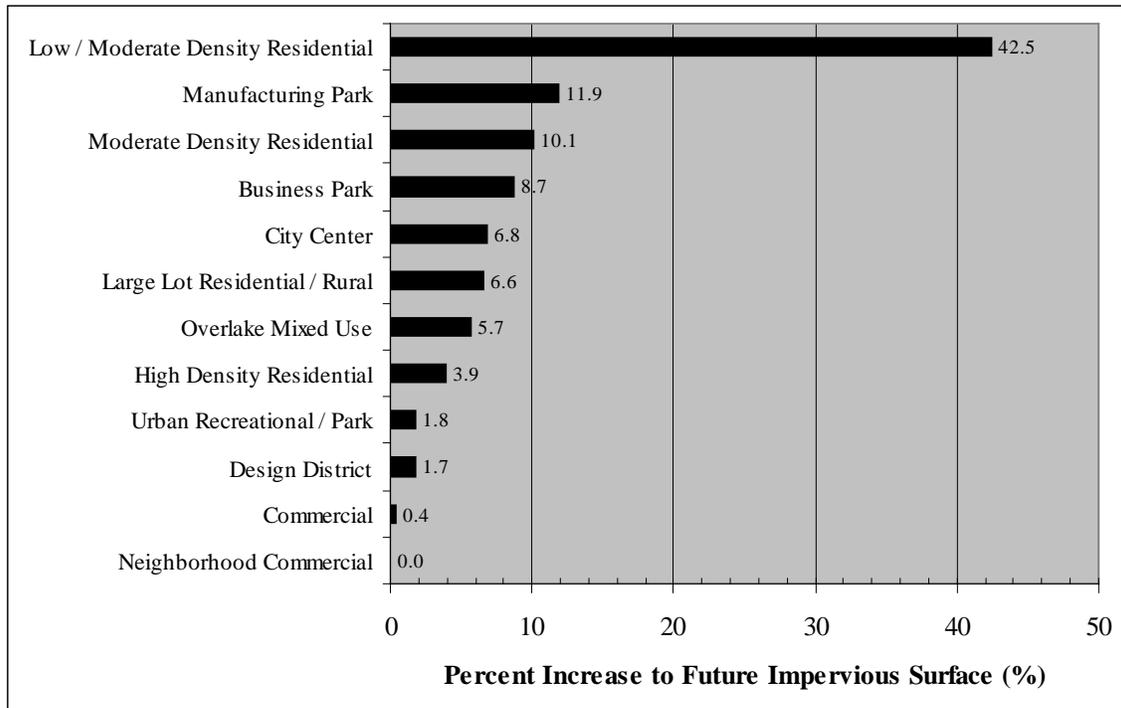


Figure 13. The relative contribution to future impervious surface growth, by land use.

The *percent contribution to future impervious surface*, by type of zoning, indicates the percent attributed to the increase in impervious surface from current to full development. So this is an estimate of the relative contribution of each type of zoning to the total estimated growth in impervious surface. Considering business park zoning, the difference between the estimated future and current level contribution to the city-wide total is 3.74 percent - 2.32 percent or 1.42 percent. Considering the relative contribution of the other types of zoning, the overall expected increase is 50.26 percent minus 33.97 percent or 16.29 percent. This is the estimated growth level in impervious surface from the current city-wide average once a build-out condition is achieved. Therefore, the increase in future impervious surface levels attributed to business park zoning is $1.42/16.29$ or .08717 (8.72 percent).

Redmond's surface waters at build-out

Changes to average impervious surface levels, associated with full development (build-out), were examined for storm water catchments with perennial surface water drainage.

Forty-three of the 92 delineated catchments, representing 87 percent of the city, have defined perennial surface water drainage. With the exception of the Sammamish River and Bear Creek (and its lower tributary Evans Creek), there are approximately 59 kilometers of surface drainage within the city. Storm water catchments with surface drainage currently have a 28 percent average impervious surface level. This level will increase to 44 percent at build-out. The build-out condition will result in an approximately 35 percent decline in stream kilometers situated in catchments with impervious surface levels below 20 percent when compared to the current condition (Table 2). That change is balanced by increases in the higher impervious surface levels, in particular, those above 50 percent where an increase of 32 percent is estimated.

Table 2. The current and future representation in impervious surface for Redmond's stormwater catchments with perennial drainage.

Impervious Level (%)	Current (2001)			Full Development (build-out)			Change in percent (%)
	Number of Catchments	Stream Length (km)	Percent of Total Length (%)	Number of Catchments	Stream Length (km)	Percent of Total Length (%)	
0-10	9	5.73	9.8	0	0	0.0	-9.8
10-20	5	19.97	34.1	4	4.92	8.4	-25.7
20-30	6	8.72	14.9	2	4.09	7.0	-7.9
30-40	9	12.28	20.9	5	18.57	31.7	10.7
40-50	5	7.12	12.1	12	7.66	13.1	0.9
50-60	4	3.84	6.6	7	14.91	25.4	18.9
60-70	5	0.95	1.6	7	6.88	11.7	10.1
70-80	==	==	==	3	1.30	2.2	2.2
80-90	==	==	==	3	0.27	0.5	0.5

Current and future water quality

The city of Redmond has collected water quality data at 41 locations since 1995, targeting the major surface water drainages within the city. The water quality data collected includes flow; temperature; dissolved oxygen; conductivity; pH; turbidity; total suspended solids; fecal coliform; total phosphorus; and total nitrogen. In many cases, the data do not share the same sampling dates or a similar sampling frequency. For example, the sampling frequency for some of the stations occurred quarterly while for others monthly. Also, sampling was conducted on a routine basis and did not specifically target storm events.

Because of the differing sampling periods among the stations, this analysis did not attempt to examine the water quality observed on a particular date or during a defined period. Instead, it focused on providing an overall characterization of water quality among the stations through the application of a water quality index, or score. The connection between water quality and stormwater runoff was achieved by examining the relationship between

the water quality score, generated for each monitoring station, and the average level of impervious surface present in their respective catchments. Among the monitoring stations, 15 were chosen for analysis since they have at least 20 sampling events associated with them (Figure 14).

As further described in the Methods section of this report, the water quality score serves as a general indication of water quality based on the concentrations and levels of seven parameters including temperature; dissolved oxygen; pH; turbidity; fecal coliform; total phosphorus; and total nitrogen. These parameters were chosen because they were collected consistently at these stations. Due to the environmental conditions present during sampling and the way the score is calculated, it is more a reflection of the water quality present at base-flow rather than storm events. The major assumption in this analysis is that chronically impaired water quality, evident at base-flow conditions, is the result of impacts associated with urbanization and increased impervious surface levels and, therefore, stormwater runoff. Ideally, the water quality of these receiving waters during storm events would have been used. Unfortunately, that data is not available (and rarely is), so this analysis is an attempt to examine the impervious surface / water quality connection using available information. (A separate analysis that examined the relationship between impervious surface and receiving water quality observed during storm events in the city of Bellevue was used to supplement this analysis. This report is titled: “Review of Storm Event Water Quality Data: City of Bellevue.” Bellevue is situated adjacent to, and west of Redmond.) (Tables summarizing the water quality data and water quality score generation are presented in Appendix C.)

Table 3 provides the representation of current land use zoning in addition to estimates of current and future (build-out) impervious surface levels associated with each of the monitored catchments.

Among the monitoring stations, the current level of impervious surface within their catchments varied between 11 percent (490080, Avondale @116th), to 42 percent (260, Villa Marina). The median impervious level among the monitored catchments is 24 percent, rising to 43 percent at a build-out condition. The majority of the catchments have the greatest development intensity levels in the low to moderate levels, consistent with current zoning. Exceptions are Villa Marina (260) which, due to its land use zoning for commercial development (the Overlake mixed use forms 73 percent of its area), could result in impervious surface levels reaching 68 percent in the future. Catchment 30 (116th Street Ditch) also has a high representation of business park zoning (35 percent), balanced by urban recreation. Also, catchment 490140 (Perrigo) has a more equitable balance of residential development levels in comparison to the other catchments.

Figure 15 presents the relationship between the water quality score and the average level of impervious surface estimated for each of the monitored catchments. The general trend in the relationship indicates that as impervious surface levels increase in the catchments, the overall water quality, as indicated by the water quality score, declines. (Lower scores are indicative of higher water quality.) A water quality score of 0 reflects median values for the water quality parameters evaluated. The average level of impervious surface within the

city of Redmond is 34 percent, 9 percent above the impervious level that results in a water quality score of 0.

As observed in Figure 15, several locations had better water quality than expected, given their level of impervious surface (enclosed within box). These stations include: catchments 640 (Redmond 74), 90 (Peters Creek at 87th) and 320 (Idylwood Creek). To examine why this is the case, these catchments and their receiving waters were further examined.

The initial analysis examined the level of impervious surface as a catchment average. This assumes that the distribution of impervious surface is relatively uniform across the catchment. To examine whether this is a correct assumption, the level of impervious surface within a closer proximity to the stream was determined. Initially, a 300-foot (91.4 meter) buffer was placed around each of the monitored streams. Then, the buffer was used to clip the impervious surface grid. From this information, the average level of impervious surface occurring within buffers, inclusive to each catchment, was determined.

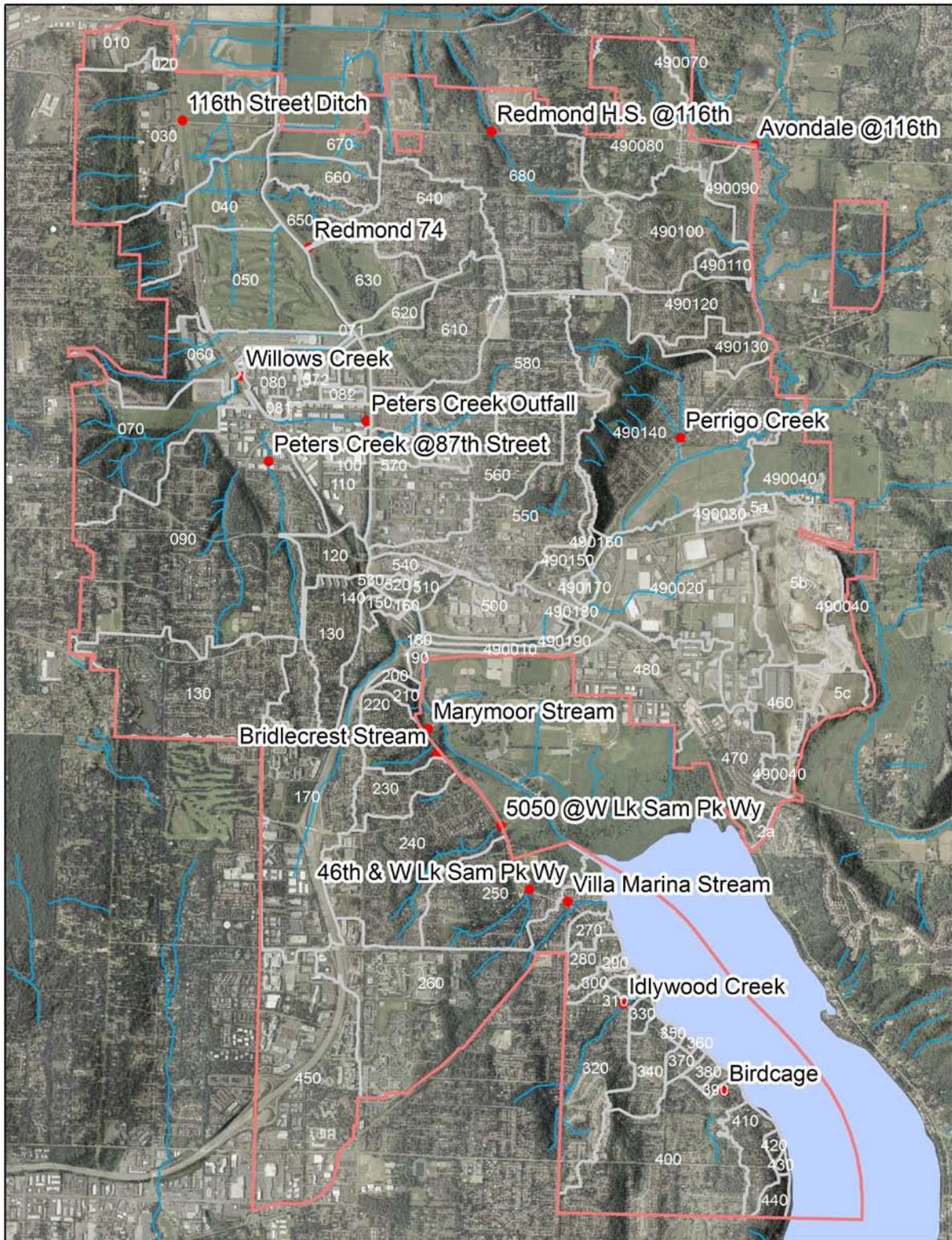


Figure 14. Water quality monitoring locations and storm water catchments (numbered).

Figure 15 also includes the relationship between the level of impervious surface within the 300-foot buffer for each monitoring location and its associated water quality score. Comparing the relationships presented in Figure 15, it is evident that there is a close association between the water quality score and level of impervious surface, whether examined based on a stream buffer or catchment-wide basis. This indicates that for the majority of the stations, the distribution of impervious surface is fairly uniform throughout most of the catchments examined. Overall, the average impervious surface level observed within the 300-foot buffer was about 27 percent, slightly higher than that estimated on a catchment basis. This indicates that, in most cases, riparian buffers fared no better than the rest of the landscape from the effects of development and the generation of impervious surfaces.

Table 3. The representation of land use zoning within the study catchments along with estimates of current and future impervious surface levels.

Monitoring Station (Catchment No.)	Catchment Area (ha)	Current Impervious (%)	Future Impervious (%)	Neighborhood Commercial	Commercial	Design District	High Density Residential	Business Park	City Center	Urban Recreation	Moderate Density Residential	Manufacturing Park	Overlake Mixed Use	Large Lot Residential	Low/Moderate Density Residential
				Percent of City Area (%)											
116 th Ditch (30)	151	14	33	==	==	==	==	35.1	==	34.7	==	==	==	16.9	13.3
46 th & W. Sam. (250)	77	22	40	==	==	==	0.7	==	==	==	3.6	==	==	14.3	81.4
5050 (240)	104	30	42	==	==	==	10.9	==	==	==	11.8	==	17.1	0.4	59.8
Avondale @116th (490080)	90	11	43	0.1	==	==	==	==	==	==	2.2	==	==	==	97.7
Birdcage (400)	112	30	43	==	==	==	==	==	==	==	==	==	==	==	100
Bridlecrest (220)	28	18	43	==	==	==	==	==	==	==	==	==	==	==	==
Idylwood (320)	63	37	43	==	==	==	==	==	==	==	==	==	==	==	100
Marymoor (220)	28	18	43	==	==	==	==	==	==	==	==	==	==	==	100
Perrigo (490140)	203	20	37	==	0.7	==	14.0	0.2	==	==	11.2	==	==	37.4	36.4
Peters @87 th (90)	292	38	51	==	==	==	==	==	==	==	==	==	==	==	==
Peters (Outfall) (90)	292	38	51	==	0.3	==	12.3	2.4	==	==	0.2	13.6	==	==	71.2
Redmond 74 (640)	70	35	40	==	==	==	==	==	==	0.3	==	==	==	9.3	90.4
Red H.S. @116th (680)	187	13	38	==	==	==	==	==	==	==	==	==	==	17.9	82.1
Villa Marina (260)	147	42	68	==	==	==	4.5	==	==	==	12.6	==	72.6	2.5	7.9
Willows@Willows (70)	99	24	54	==	==	==	==	6.4	==	==	==	25.9	==	0.1	67.6

Among the three outliers, in particular, catchment 640 (Redmond 74) had considerably lower impervious surface levels in proximity to the channel in comparison to the catchment average. The average impervious surface level evaluated on a catchment basis was 35 percent, which when examined based on buffer width was 14 percent, a 21 percent difference. Among the stations, the median difference between the impervious surface level based on the catchment and buffer averages was 6 percent. Surface flow in catchment 640 originates from groundwater discharge occurring between the upper terrace and current floodplain of the Sammamish River. Due to this setting, there is a disparity in the distribution in impervious surface within the catchment. Only low levels of development occur in direct proximity to the creek, with the majority occurring in the upper portions of the drainage. This is an unusual situation among these stations, where development tends to be fairly evenly distributed throughout the catchment. While the other two outlying stations also had lower impervious surface levels within their buffers (both lower by 11 percent), other factors have a greater influence on water quality.

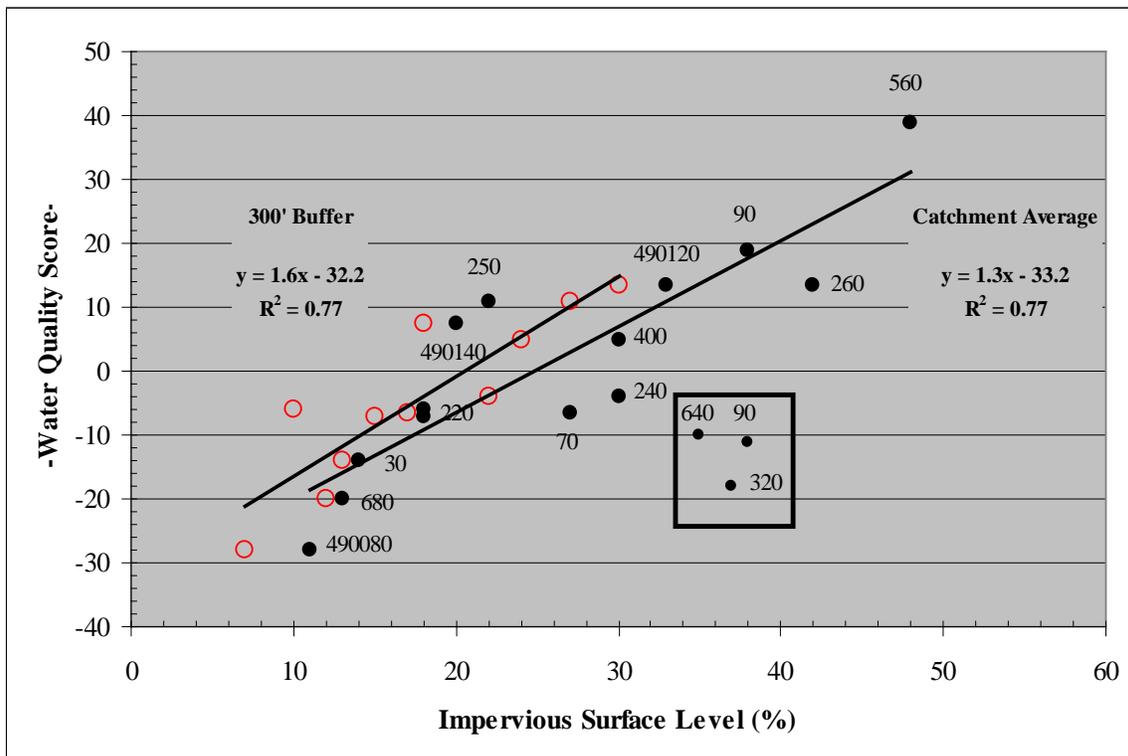


Figure 15. The relationship between percent impervious surface and the water quality score within monitored stormwater catchments.

What distinguishes catchments 90 and 320 are that both have stormwater bypass systems that collect and re-route flow within the catchment, ultimately reducing impacts to these streams. These bypass systems have the net effect of reducing effective impervious surface levels throughout the catchment by reducing stormwater inflow, and are likely one of the primary reasons why these stations have higher water quality, given their average catchment impervious surface levels, in comparison to the other monitoring stations.

Figure 15 includes the least squares regression for the relationship between impervious surface (based on both the buffer and catchment-wide assessment) and the water quality score. (Due to the reasons described above, catchments 90, 640, and 320 have been eliminated from these relationships.)

Table 4 provides an overview of the median values of the water quality parameters observed for several ranges in impervious surface. Included in Table 4 are the Washington State Class AA water quality criteria that apply to Redmond's surface waters. Referring to Table 4, water quality impairment is evident, as indicated by the exceedance of water quality criteria, even within the lowest impervious surface range, 10≤20 percent. Degradation of water quality, as indicated by increasing temperature, pH, total phosphorus and total nitrogen concentrations, occurs with increased levels of impervious surface. Dissolved oxygen and turbidity are less sensitive to increased impervious surface levels. Among the water quality parameters evaluated, Washington State criteria apply to temperature, dissolved oxygen, pH, turbidity, and fecal coliform.

Based on the median water quality characteristics, water quality criteria are only met for some parameters at percent impervious levels below approximately 20 percent (Figure 15 and Table 4). Above this level, chronic water quality impairment is evident. This analysis is based on indicators of chronic impairment to water quality relying, in some cases, on data observed during the summer months. It is expected that water quality impairment would be greater for some water quality parameters during storm events, proportional to the level of impervious surface present. The underlying assumption is that greater levels of impervious surface present within catchments result in greater adverse impacts to water quality across a range of parameters. While these impacts are likely more evident during storm events, at base flow conditions they persist as chronic impairment.

Missing from this assessment is an accounting of what stormwater best management practices (BMP) are in place in each of these catchments and what effect they have on water quality. While not considered a best management practice, the stormwater bypass systems present in catchments 90 (Peters) and 320 (Idylwood) appear to have altered the typical impervious surface / water quality relationship. What about the other stations? That this factor can be largely ignored in assessing this relationship suggests that stormwater BMPs, currently in place, are not providing adequate levels of protection.

Important in this consideration is an understanding of the period that development occurred within the various catchments. This is because much of Redmond was developed at a time when the expectations for the storage and treatment of storm water were considerably lower than they are currently. Also, the type and representation of the impervious surfaces present is an important consideration. For instance, in many cases, a high representation of road surfaces (typically completed at an early development phase) results in a greater portion of the total stormwater runoff draining directly to receiving waters, bypassing any storage and treatment. What is required is an understanding of the paths from flow-generating surfaces to receiving waters, considering the intermediary storage and treatment processes present, if any. Unfortunately, urban drainage infrastructure, due in part to its chronologically fragmented construction, is not well

documented. These, and other factors, result in increased difficulty in providing adequate solutions that address stormwater runoff impacts, particularly in an urbanized area such as Redmond.

Table 4. Median water quality concentrations and scores, by impervious surface range.

Catchment Impervious Range (percent)	n	Water Quality Score	Impervious Surface (%)	Geo. Mean Fecal Coliform (cfu/100ml)	Max Temp. (C)	Min DO (mg/L)	Max pH	Median Turbidity (ntu)	Median TP (ug/L)	Median TN (ug/L)
10<=20	5	-14	14	126	15.6	7.5	8.1	3.8	49	744
20<=30	3	7.5	22	426	16.7	7.3	8.3	4.5	54	1160
30<=40	4	9.3	32	328	18.2	5.0	8.6	3.3	61	1048
40<=50	2	26.3	45	660	18.7	6.5	8.8	4.1	78	1373
Overall Median	14	0.5	25	179	17.8	7.2	8.3	3.7	61	1048
Class AA				50	16.0	>9.5	6.5-8.5			

Conclusions: strategies to reduce impervious surface

Currently, Redmond is at an advanced stage of development, with an average impervious surface level of 34 percent. At build-out, this level is estimated to reach 50 percent, a further 47 percent increase from current levels. This projected increase is based on the status quo of current development practices, that is, impervious surface levels associated with the various land use zoning remaining at the sampled levels. However, what if Redmond were to require future development to implement low-impact development measures aimed at reducing impervious surface levels? If that were to occur, are there particular land uses that could be targeted that result in significantly greater reductions to future impervious surface levels than others?

Table 5 presents the effect on the estimated build-out impervious surface level for the city, with sequential reductions in each land use zoning type’s respective impervious surface level (*read horizontally for each zone*). Table 5 also provides the accumulative impervious surface reduction (in percent reduction from the future total), assuming uniform reductions across all land-uses (*read vertically*). For example, a 20 percent reduction in each zone’s associated impervious surface level would result in an overall 6.47 percent reduction in the estimated city-wide build-out impervious surface level (from 50.3 percent to 47.0 percent). As observed in Table 5, even if a highly ambitious 50 percent reduction were achieved across all land-uses, resulting in a 16.2 percent reduction in the future growth in impervious surface, an increase of about 24 percent is still projected from current levels.

For many of the types of land-use zoning, it appears that little can be done to reduce the estimated growth in impervious surface levels just through alteration to future development practices. This is primarily due to the current advanced level of city development. Referring to Table 1, there are limited options for those land-use zones with current high build levels and/or those representing a relatively small area of the city such as commercial, neighborhood commercial, design district, city center, high-density residential, and Overlake mixed use.

Table 5. The effect of sequential reductions in future impervious surface, by land use, on estimated build-out levels.

Zoning Description	10 percent Reduction	20 percent Reduction	30 percent Reduction	40 percent Reduction	50 percent Reduction
Neighborhood Commercial	0.00	0.00	0.00	0.00	0.00
Commercial	-0.01	-0.02	-0.04	-0.05	-0.06
Design District	-0.02	-0.07	-0.13	-0.18	-0.24
High Density Residential	-0.13	-0.25	-0.38	-0.51	-0.63
Business Park	-0.28	-0.57	-0.85	-1.14	-1.42
City Center	-0.22	-0.44	-0.66	-0.88	-1.11
Urban Recreational/Park	-0.06	-0.12	-0.17	-0.23	-0.29
Moderate Density Residential	-0.33	-0.66	-0.99	-1.31	-1.64
Manufacturing Park	-0.39	-0.77	-1.16	-1.55	-1.94
Overlake Mixed Use	-0.19	-0.37	-0.56	-0.74	-0.93
Large Lot Residential/ Rural	-0.21	-0.43	-0.64	-0.86	-1.07
Low/Mod. Density Residential	-1.38	-2.77	-4.15	-5.53	-6.91
Decrease from Build-Out (%) (Accumulative Total)	-3.22%	-6.47%	-9.73%	-12.98%	-16.24%
Estimated Build-Out Impervious Surface (%)	48.7%	47.0%	45.4%	43.8%	42.1%
Percent Increase in Impervious Surface from Present (%)	43.4%	38.4%	33.6%	28.9%	23.9%

Estimated city-wide build-out impervious surface level is 50.3 percent.

The greatest reductions in the growth of future impervious surfaces are associated with zones with lower current development levels (build-levels) that represent a substantial area of the city and have relatively high associated impervious surface levels. Among the various types of zoning present in Redmond, this most closely applies to the low/moderate density residential zoning. It has an associated impervious surface level of 43 percent and, while having a relatively high current build level of 64 percent, overall represents 45 percent of the city. Based on these characteristics, the low/moderate density residential zoning represents about 42 percent of the future growth in impervious surfaces city-wide (refer to Table 1).

Because of the current high build rate and/or its low representation within the city, the effect of decreasing impervious surface levels associated with neighborhood commercial, commercial, and design district zones will bring little return in lowering future growth in impervious surface. Efforts to decrease future impervious surface levels, for example through conservation of natural areas or strategies to reduce impervious surface of newly developed or re-developed areas, should be focused on business park, manufacturing park, moderate density residential and, in particular, rural and low/moderate density residential development.

Current build levels for low/moderate density residential zoning are presented in Figure 16. The greatest potential for increased impervious surface growth occurs within areas that currently have lower build levels (i.e. below 40 percent). These areas also provide the best opportunity to implement low impact-type building practices to retain a greater amount of pervious surface (and vegetation) with development. Catchment 490080, located in the northeastern portion of the city, has a high proportion of low/moderate residential

designated zoning (92 percent), much of which is currently at a low build level (22 percent). This situation provides the best opportunity in the city to implement alternative development practices. Opportunities are also present in the upper reaches of Willows Creek (catchment 70), which has an estimated build level of 33 percent.

The higher water quality observed in catchments 490080 (Avondale at 116th), 70 (Willows at Willows Road), and 680 (Redmond High School at 116th) reflects the lower average impervious surface levels present in each of these catchments. In particular, catchment 490080, though primarily represented by low/moderate density residential zoning, has yet to be developed. For this reason, its current build-level is among the lowest in the city, resulting in it having among the highest water quality characteristics of the monitored surface waters.

As stated earlier, and observed from Figure 16, overall, the current build-level for low/moderate residential zoning is high at 64 percent. For this reason, focusing impervious surface management on just those catchments with low current build-levels will not provide a significant enough coverage to facilitate city-wide water quality improvements.

As observed from Table 5, given the city's current high build rate, lower reductions cannot be achieved by focusing on the reduction in impervious surface associated with just one or a few of the land-use zones while ignoring the current landscape. Rather, it will require a combination of identifying opportunities to reduce impervious surface within the current infrastructure and addressing future development practices.

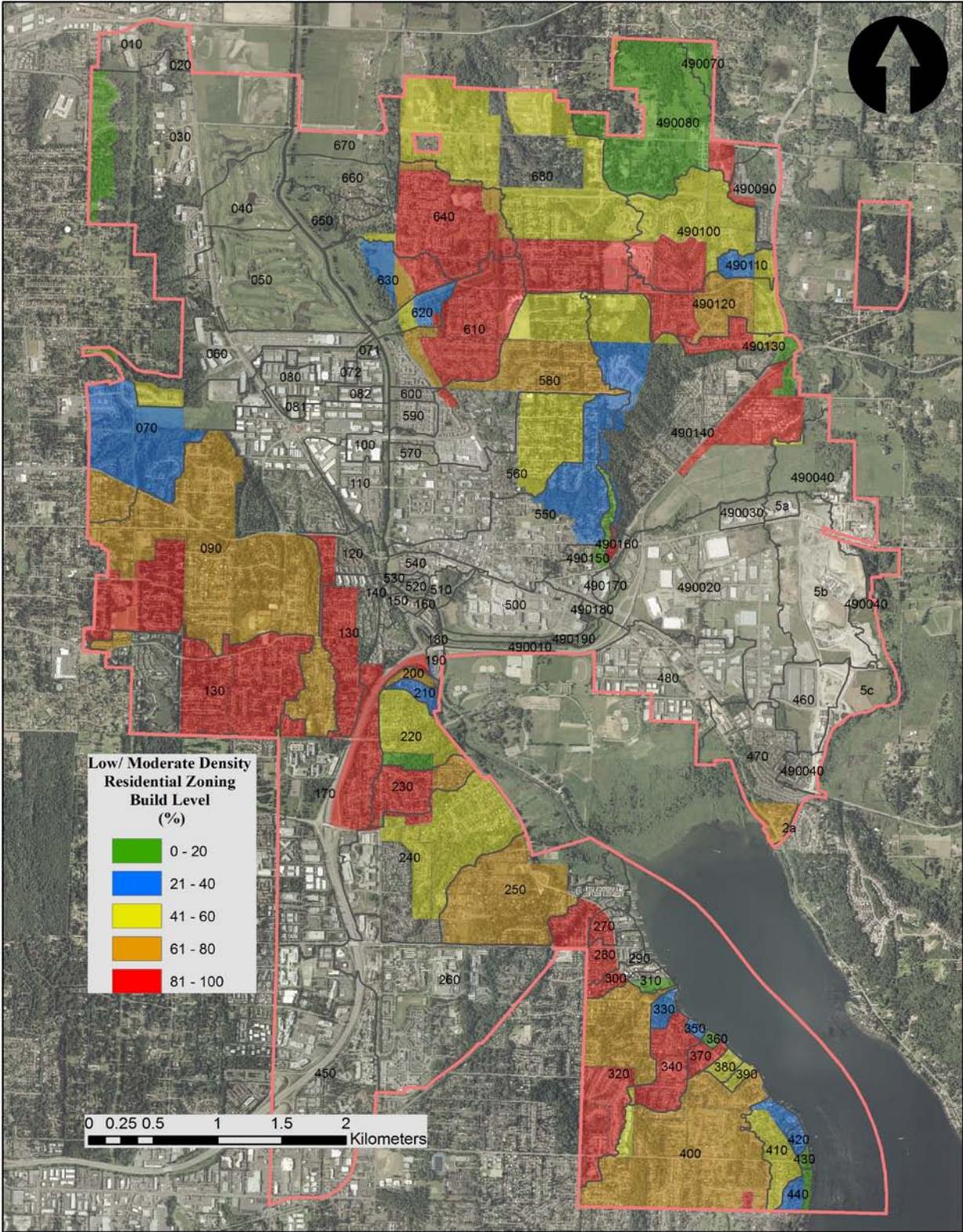


Figure 16. Build levels (%) for low/moderate residential zoning, by catchment.

References

Sanborn (Maria Fiorella). 2005. Western Washington Land Cover Change Analysis. Final Report. Prepared for: Washington Department of Ecology.

Beyerlein, Douglas; Joseph Bracher. 1998. "Traditional Alternatives: Will More Detention Work?" in Salmon in the City Conference Proceedings. American Public Works Association, Washington Chapter. Mount Vernon, Washington. May 20-21, 1998.

Northwest Hydraulic Consultants (NHC). 2006. Redmond Landscape Level Modeling Summary Report. Prepared for the City of Redmond Public Works, Natural Resources Division, by Patty Dillon and David Hartley, NHC, Seattle, Washington.

Appendix A: Additional Figures

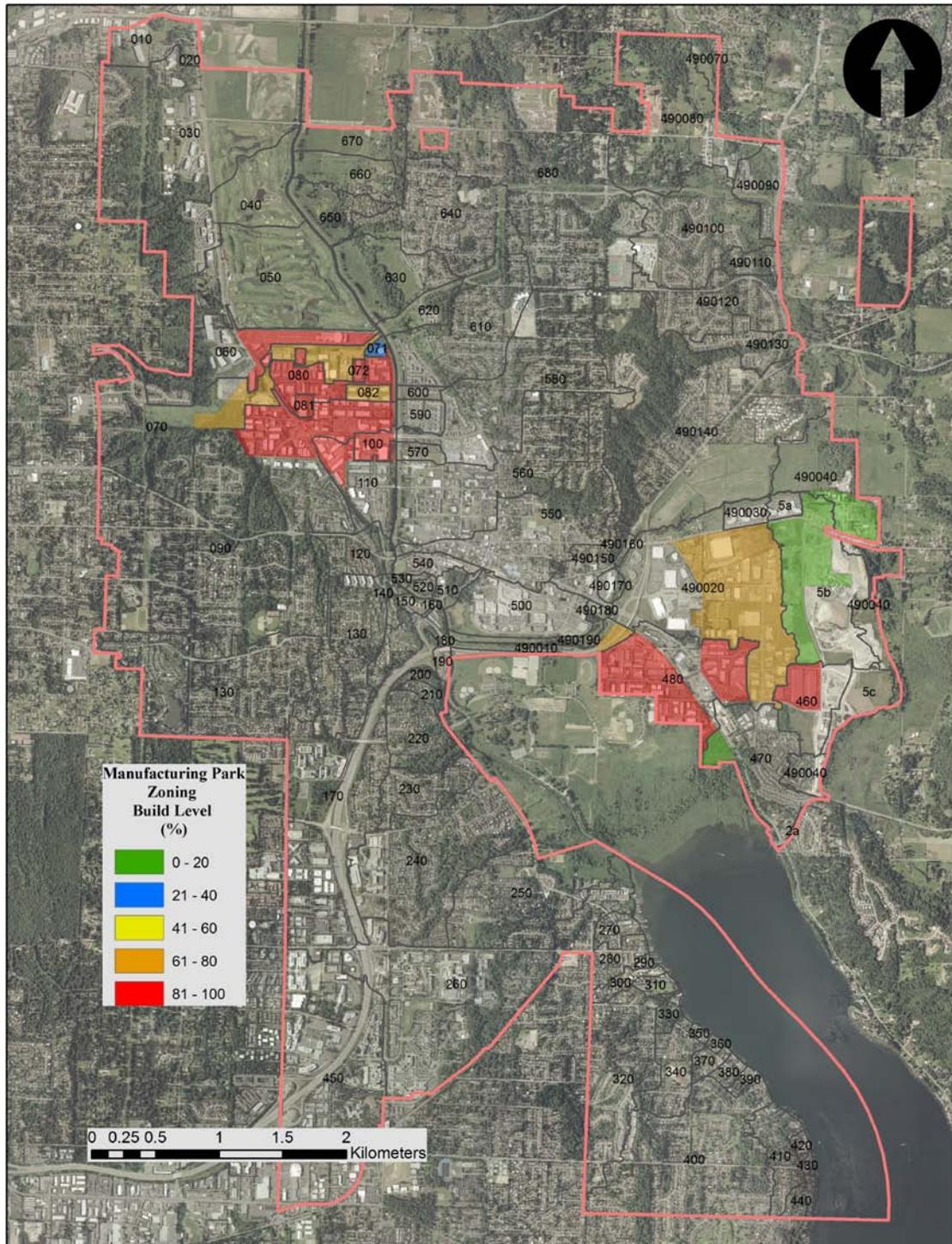


Figure A-1. Build levels estimated for manufacturing park zoning.

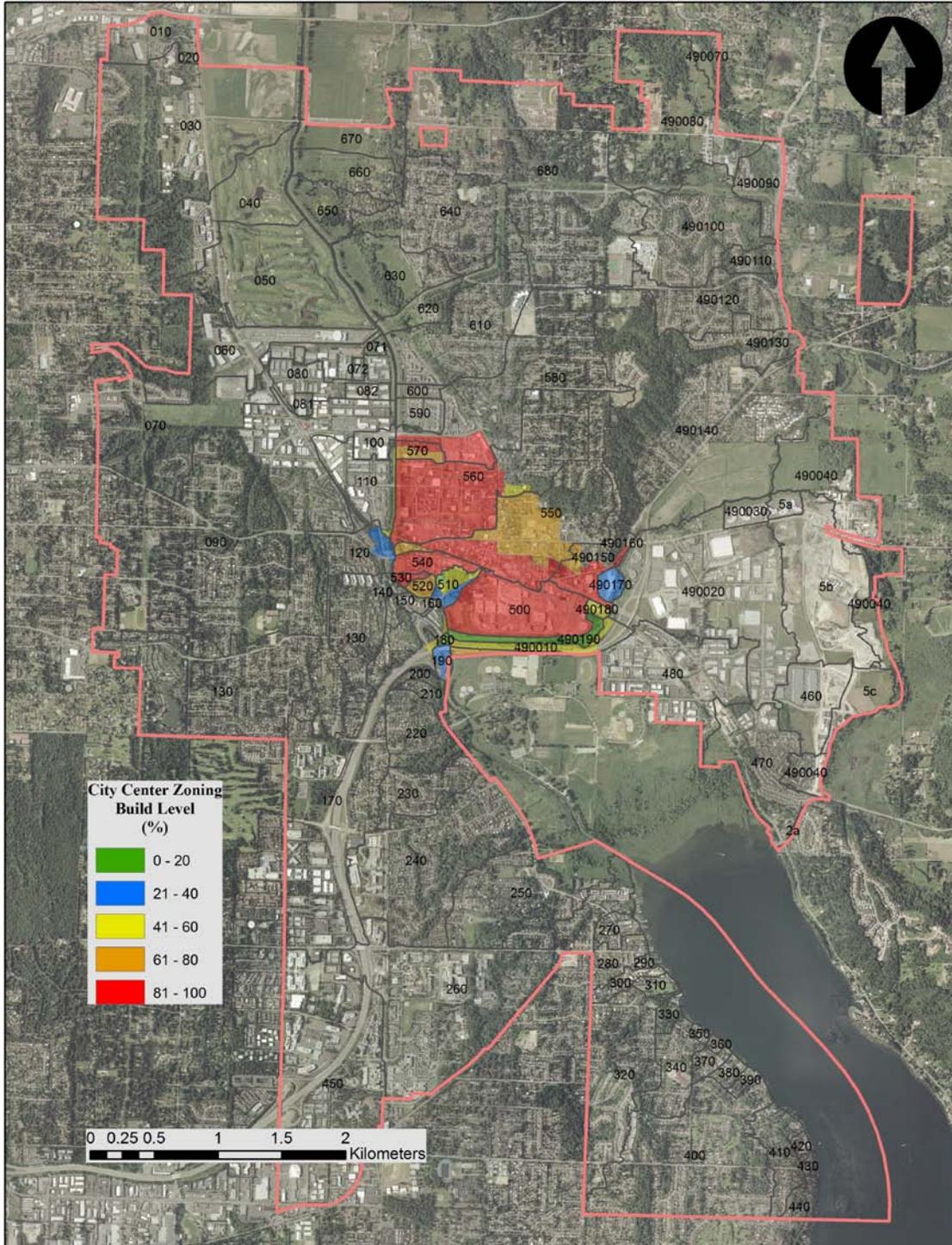


Figure A-2. Build levels estimated for city center zoning.

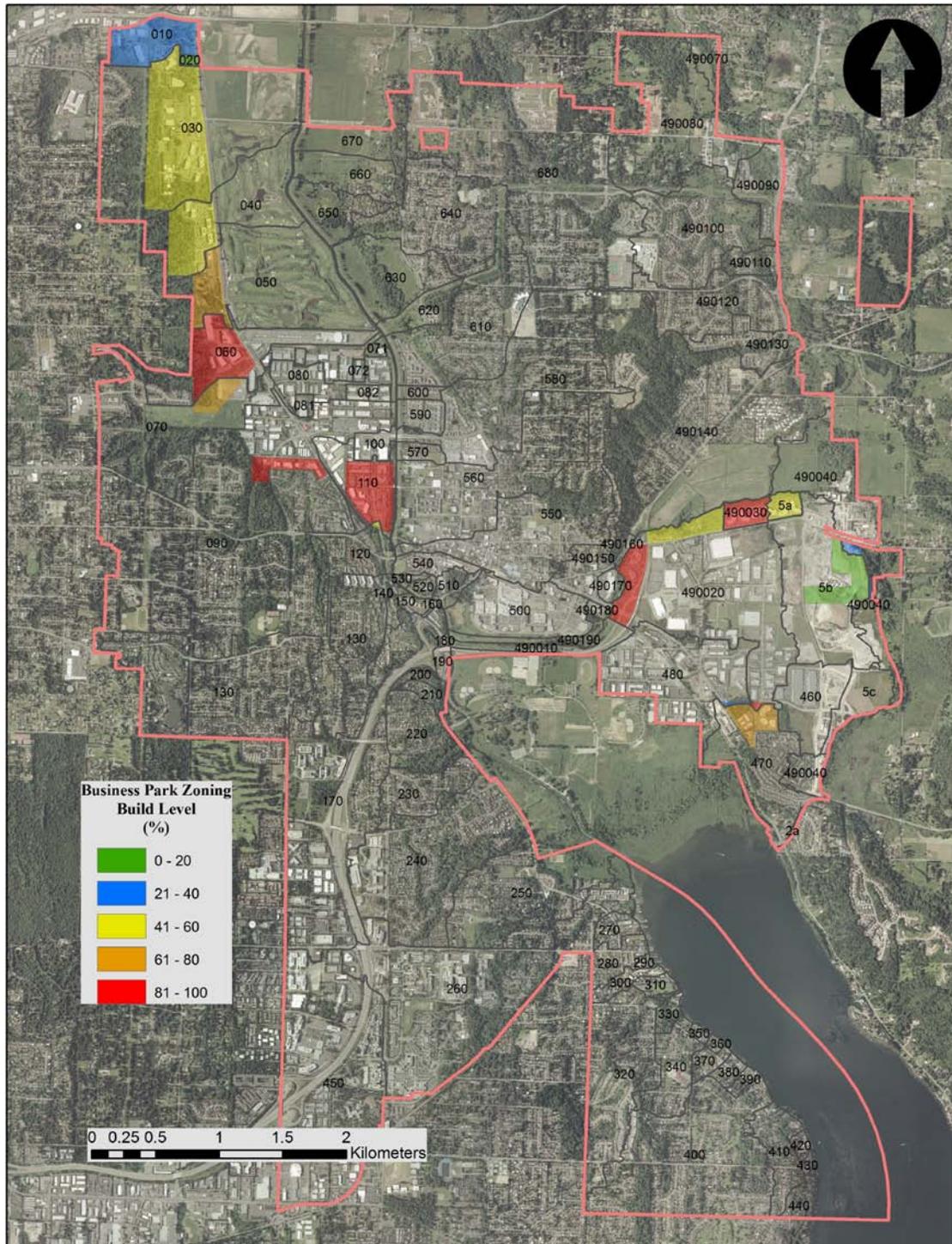


Figure A-3. Build levels estimated for business park zoning.

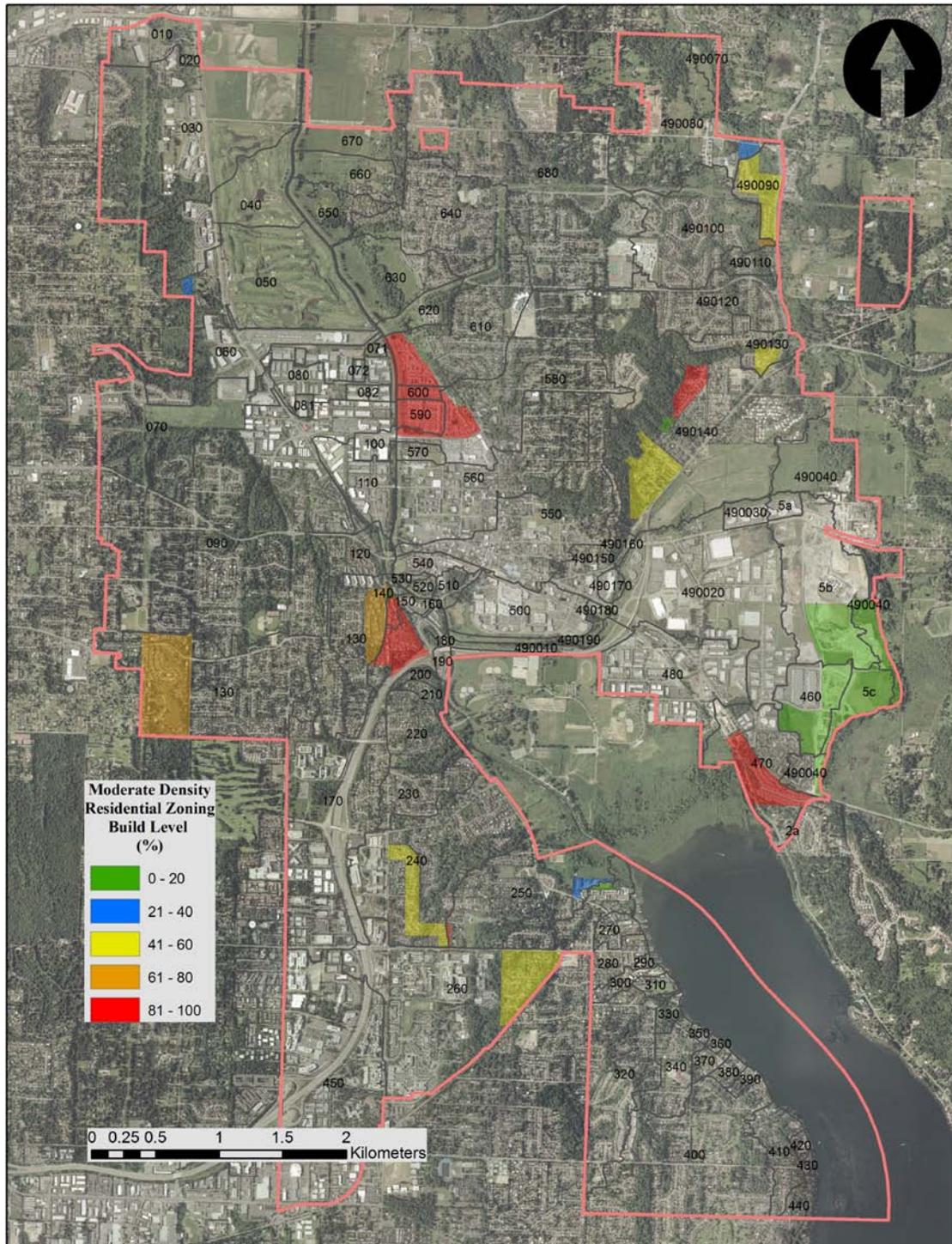


Figure A-4. Build levels estimated for moderate density residential zoning.

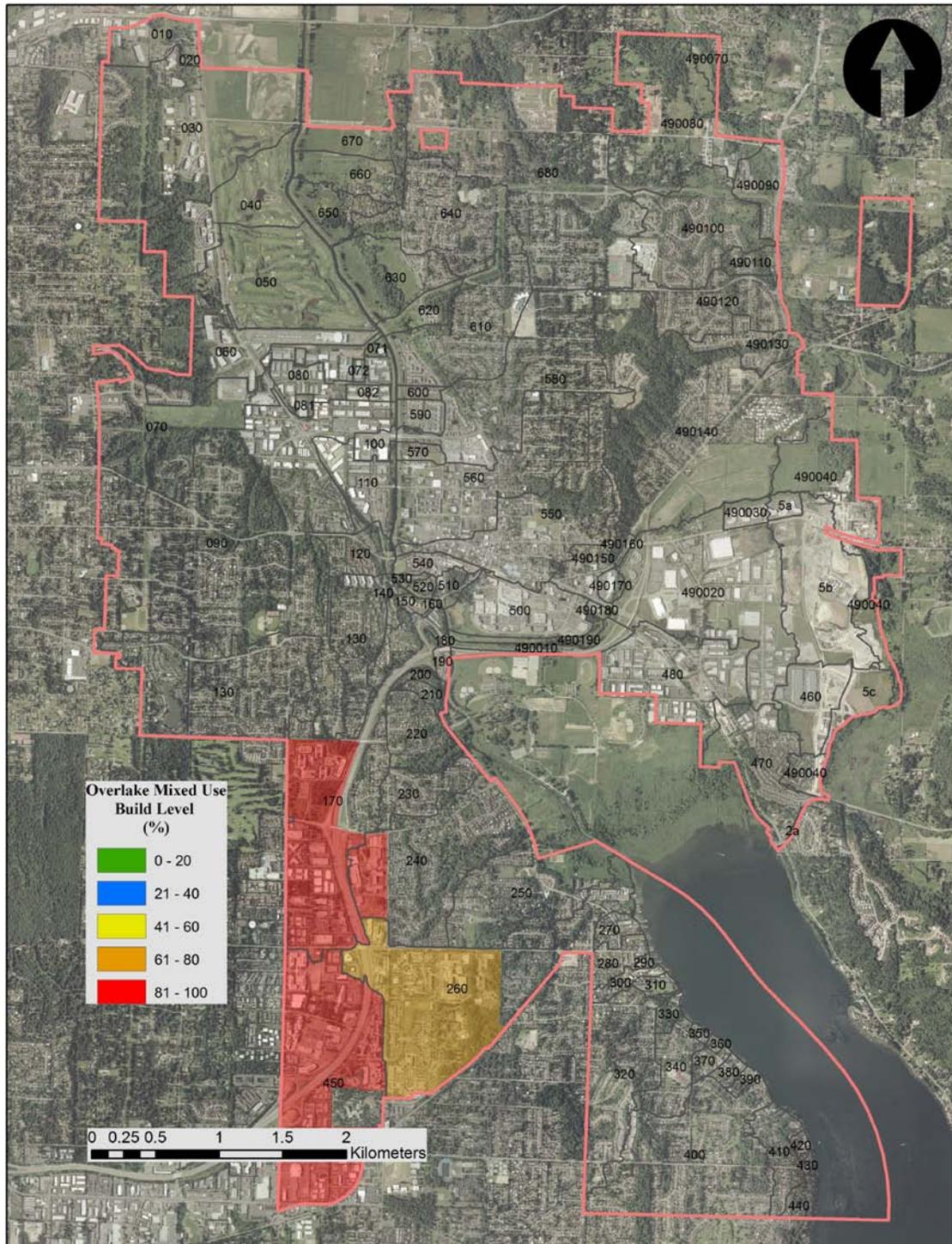


Figure A-5. Build levels estimated for Overlake mixed use zoning.

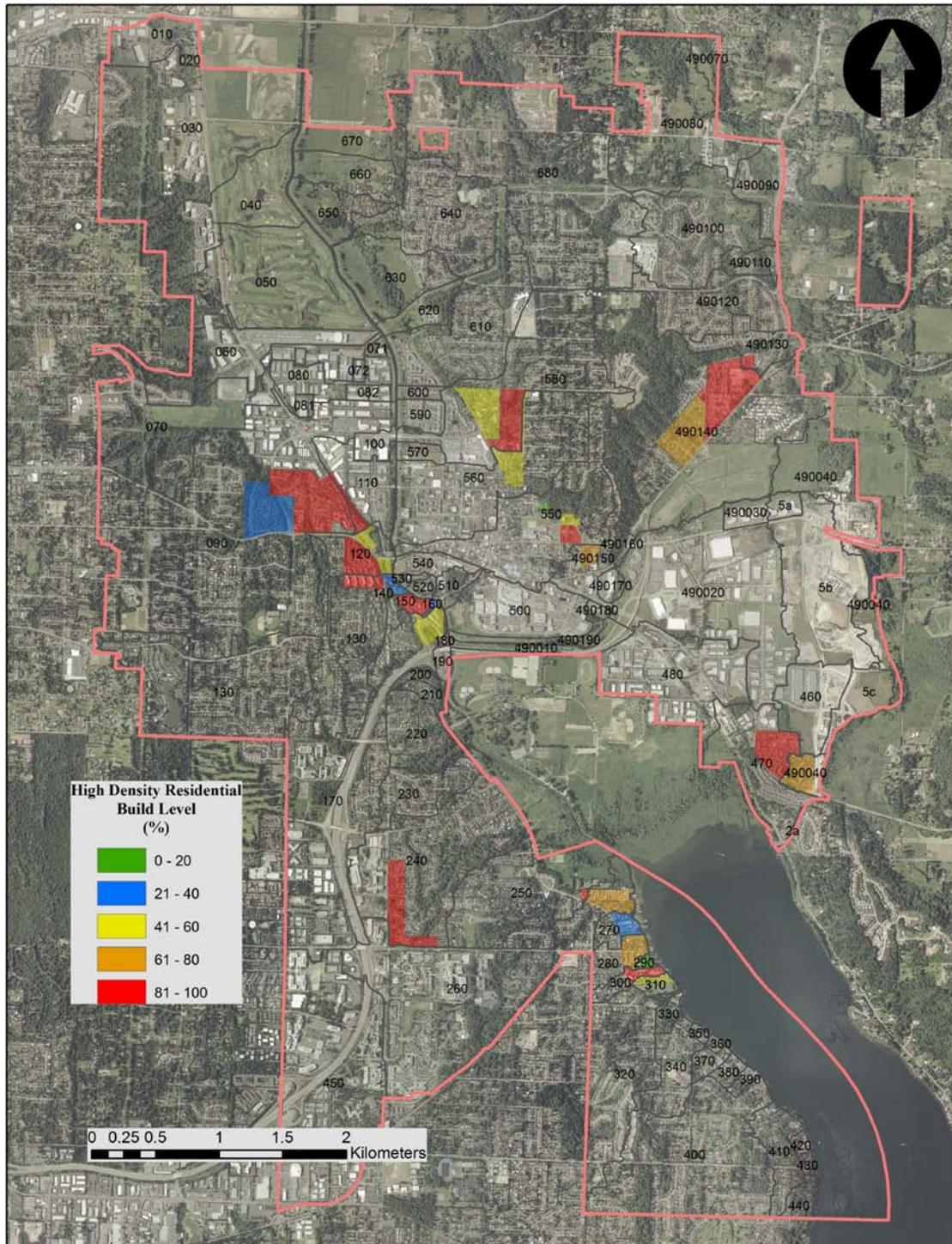


Figure A-6. Build levels estimated for high density residential zoning.

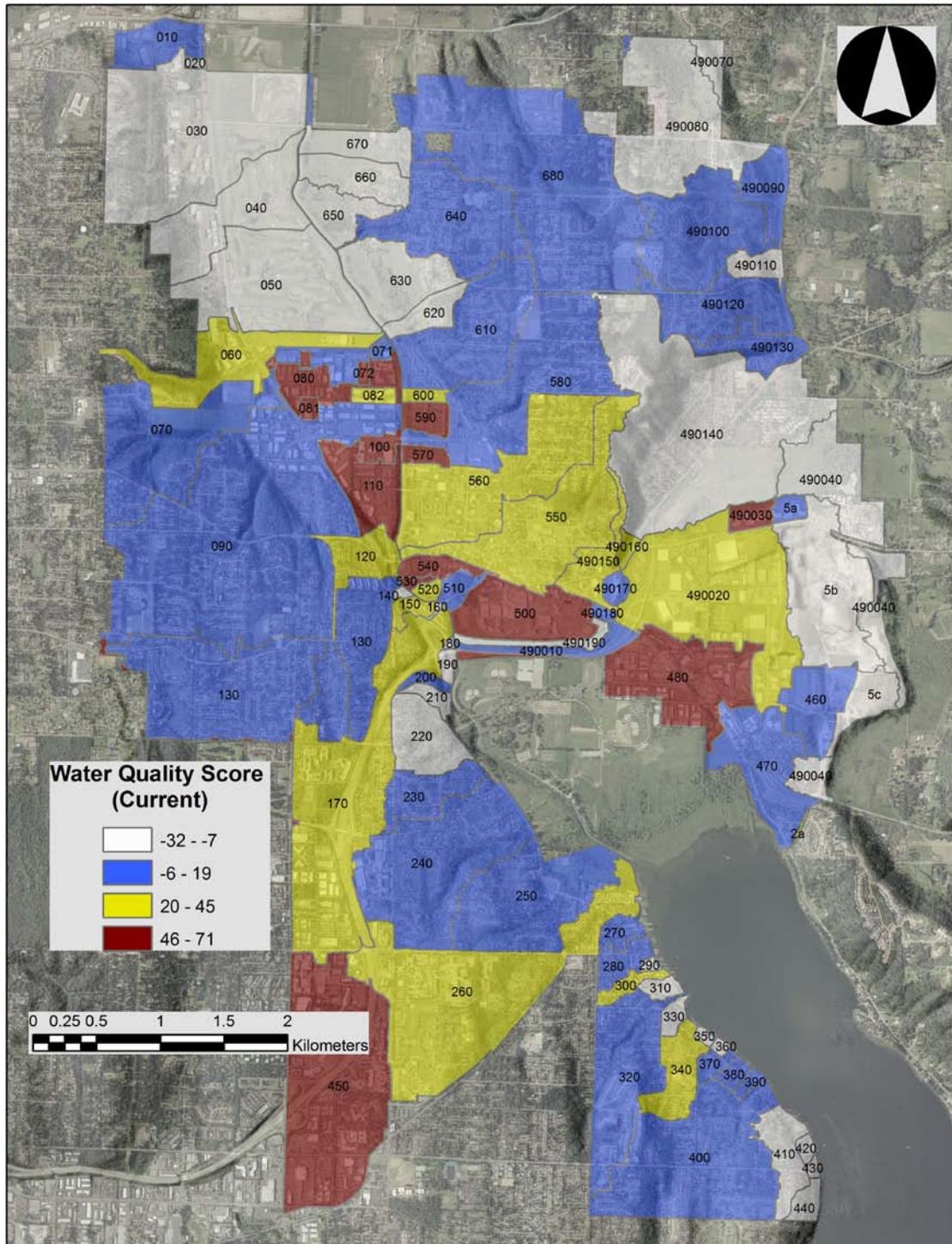


Figure A-9. Ranges in catchment water quality scores based on current (2001) average impervious surface levels. (Lower scores are indicative of higher water quality.)

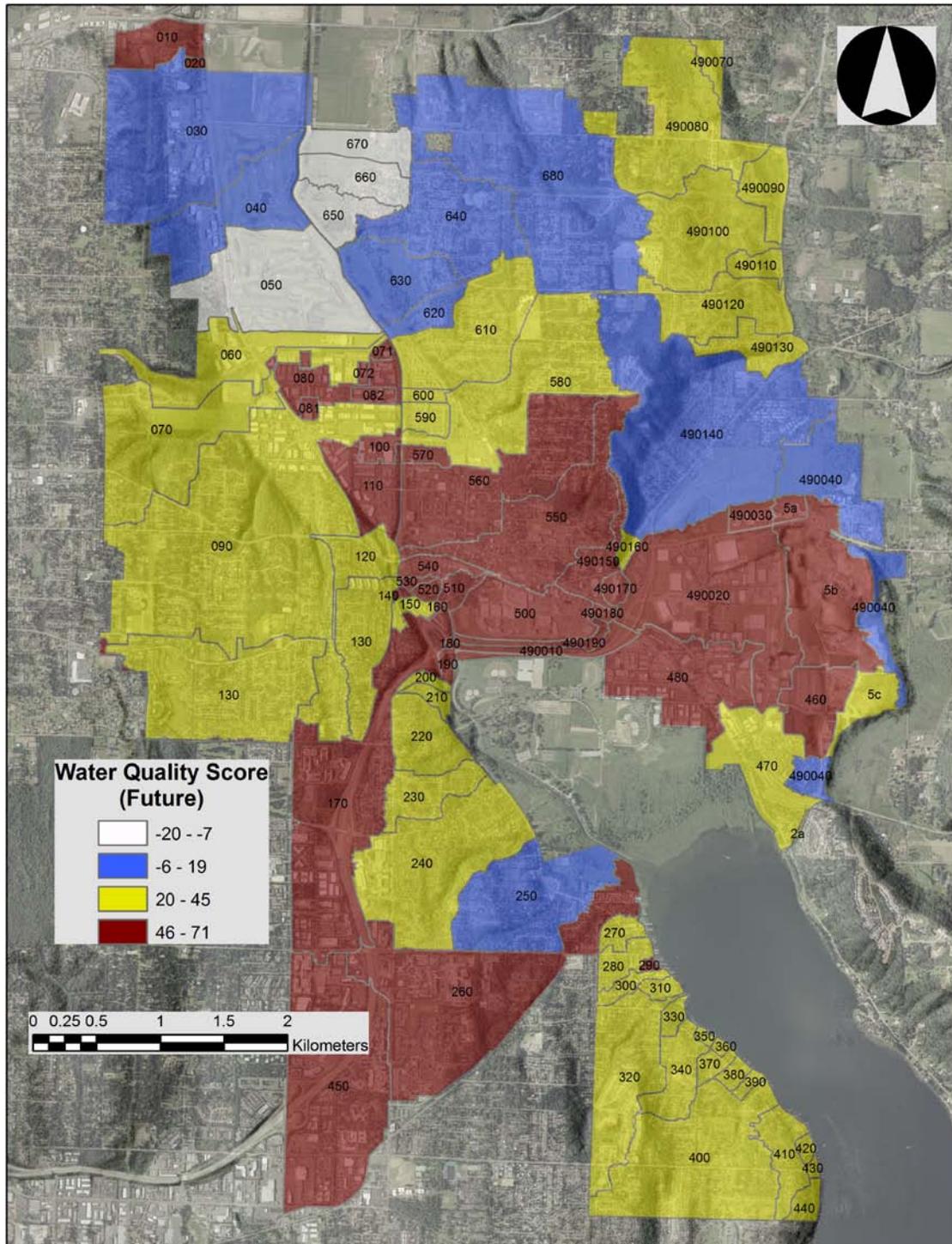


Figure A-10. Ranges in catchment water quality scores based on future (build-out) estimated average impervious surface levels. (Lower scores are indicative of higher water quality.)

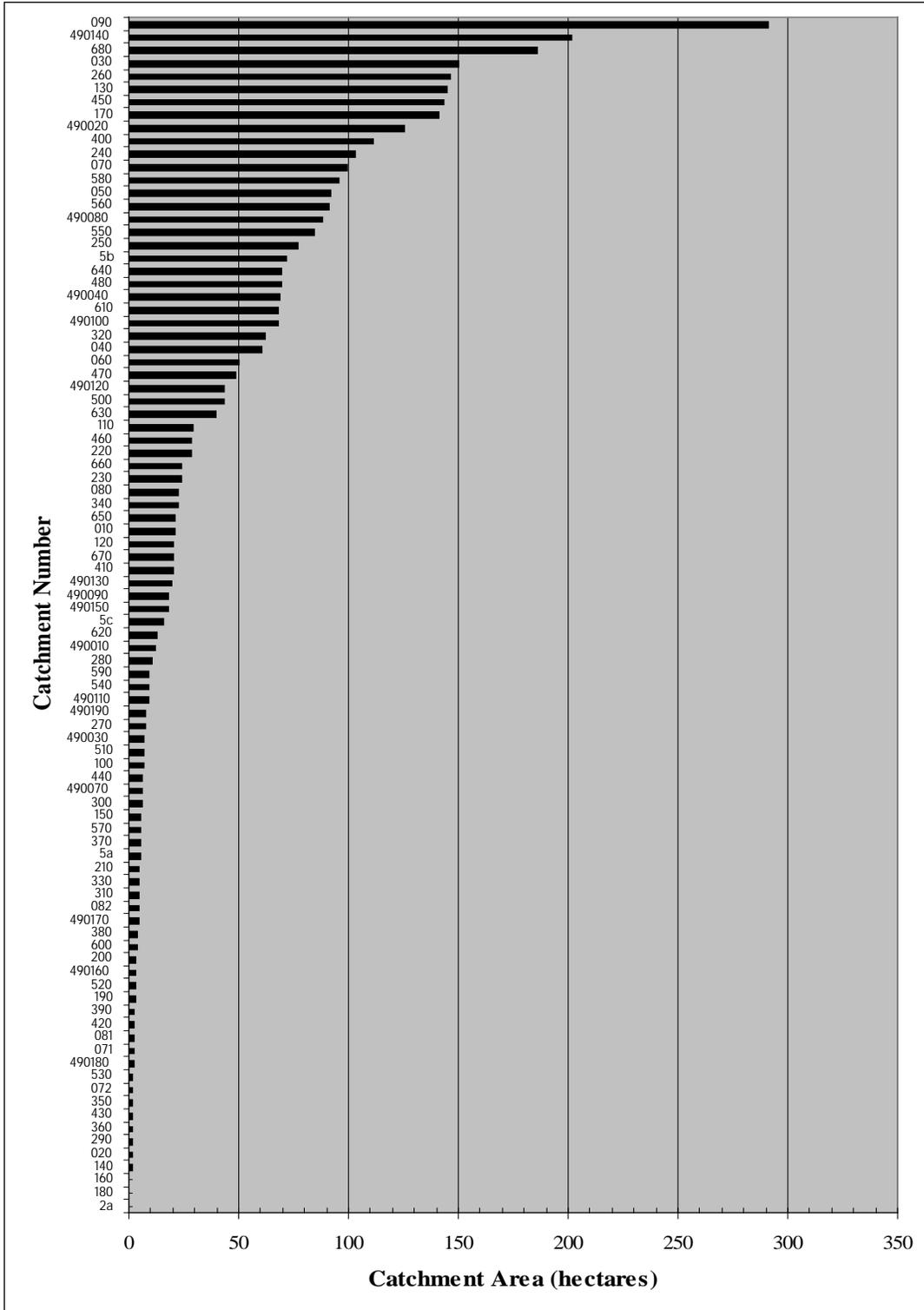


Figure A-11. Area of Redmond's storm water catchments (in hectares).

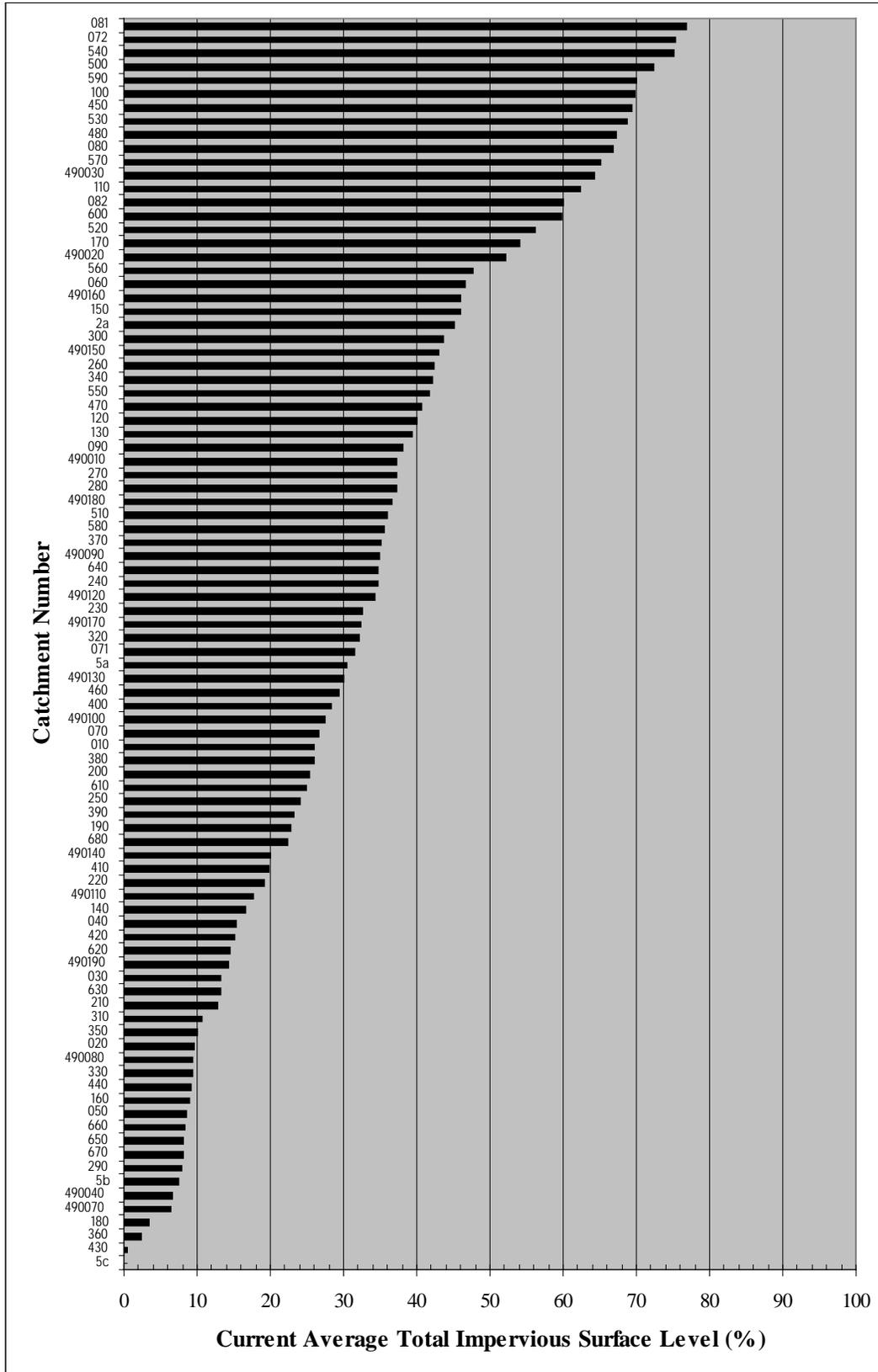


Figure A-12. Current average impervious surface levels of storm water catchments.

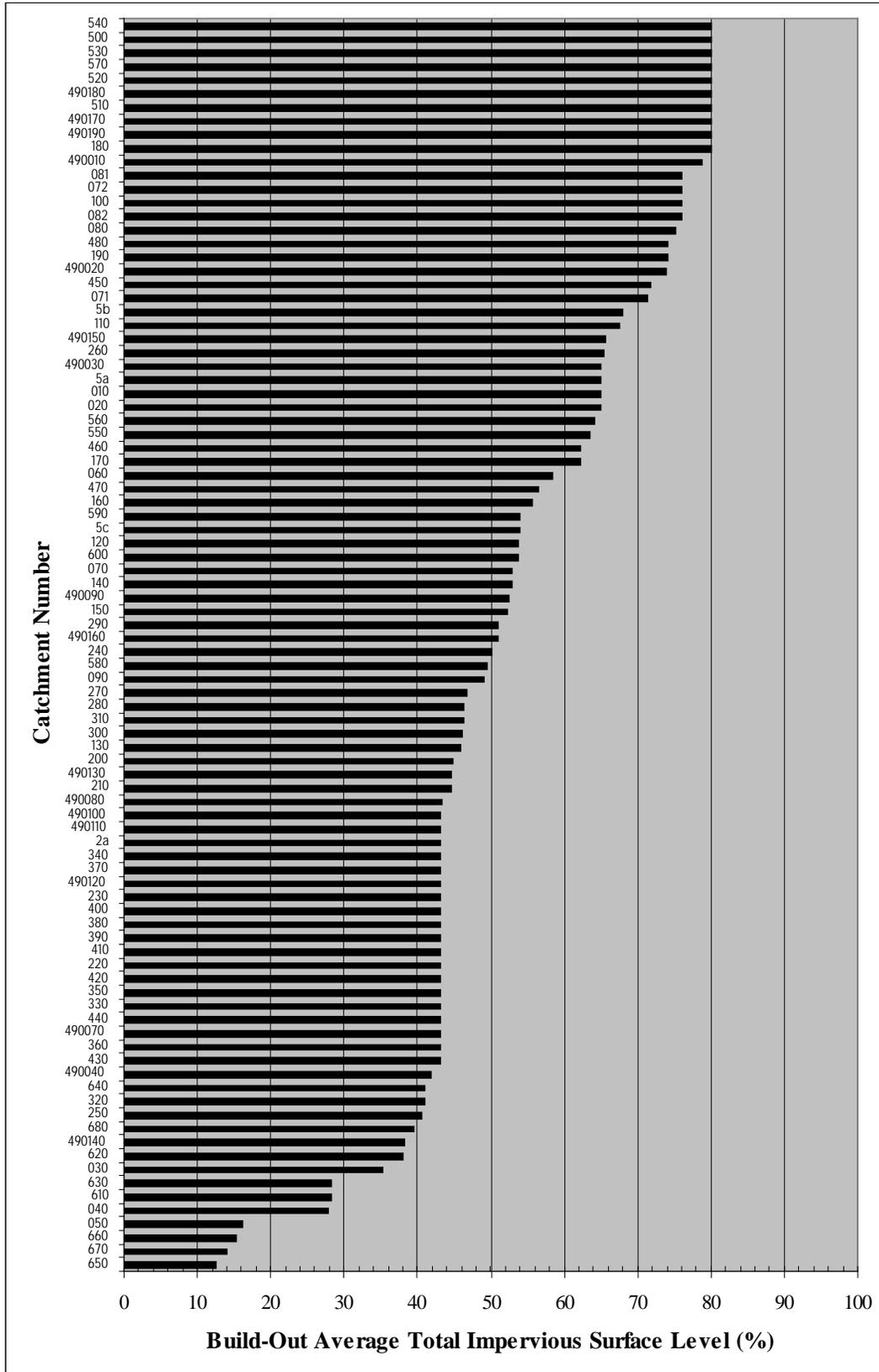


Figure A-13. Build-out average impervious surface levels of storm water catchments.

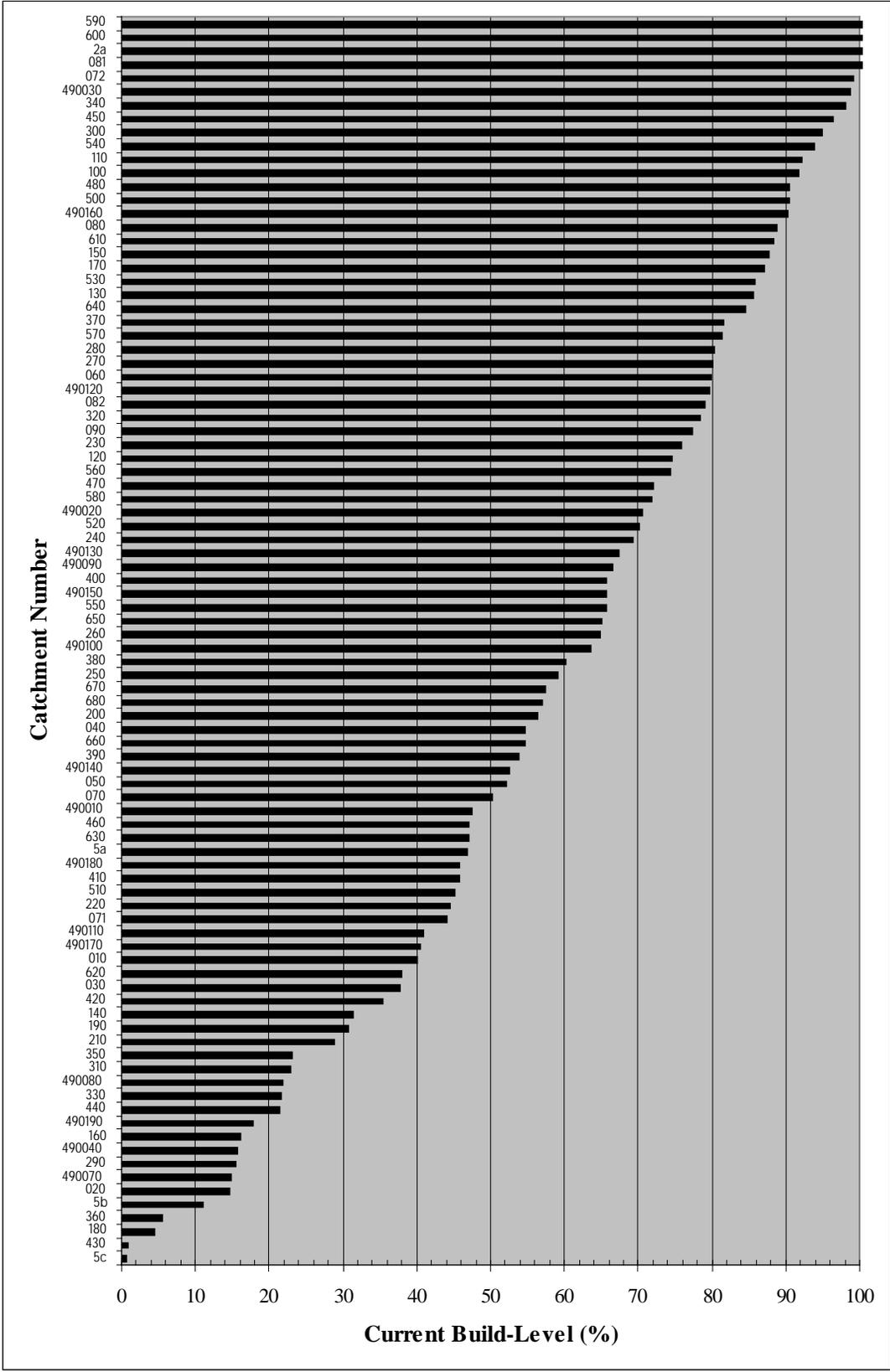


Figure A-14. Current build level of storm water catchments.

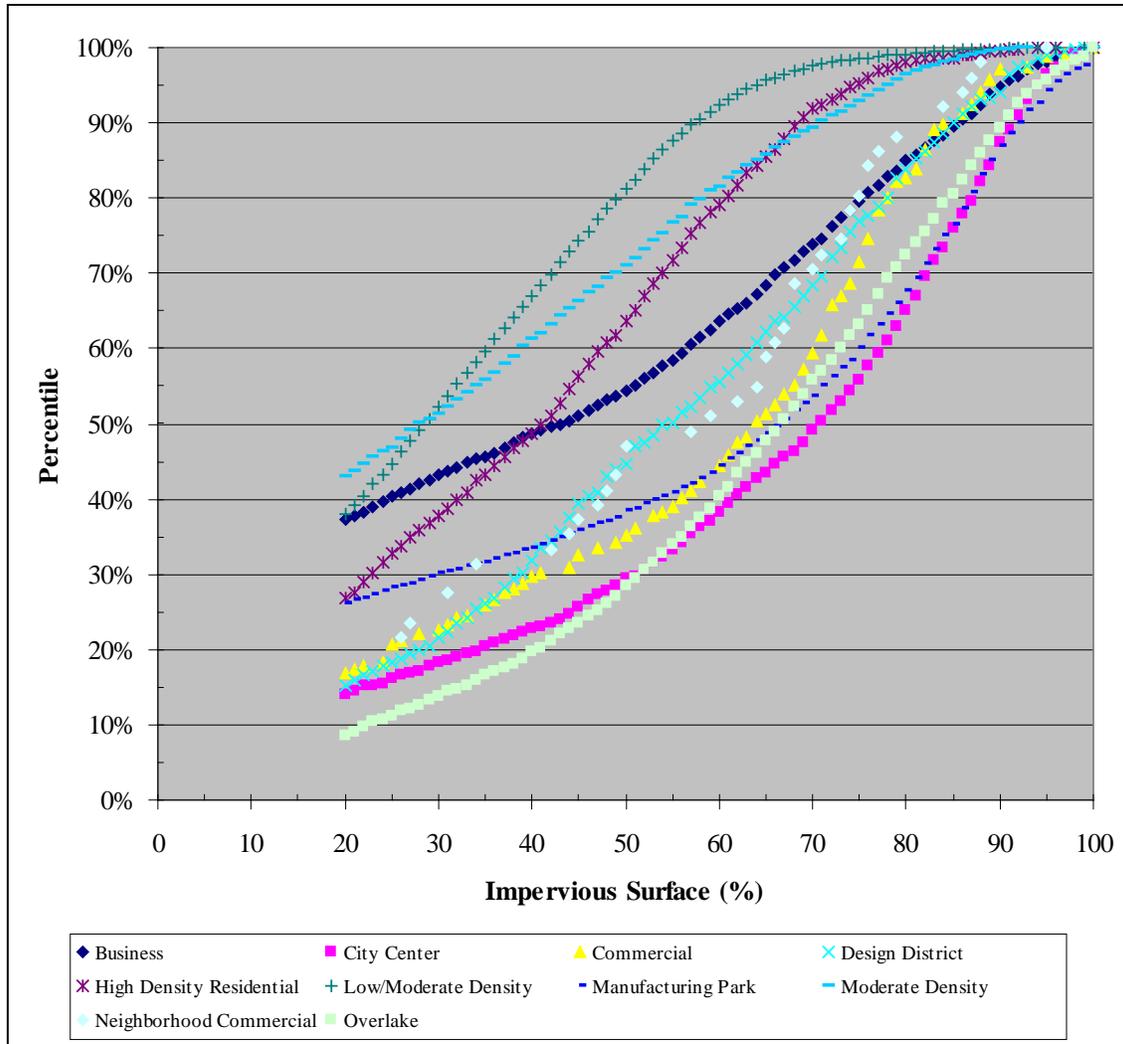


Figure A-15. Cumulative frequency distribution of total impervious surface levels (%) present within each land use designation. (Analysis based on 30 m² grid approximations. The grid used in this assessment set all designations below 20% at 0.)

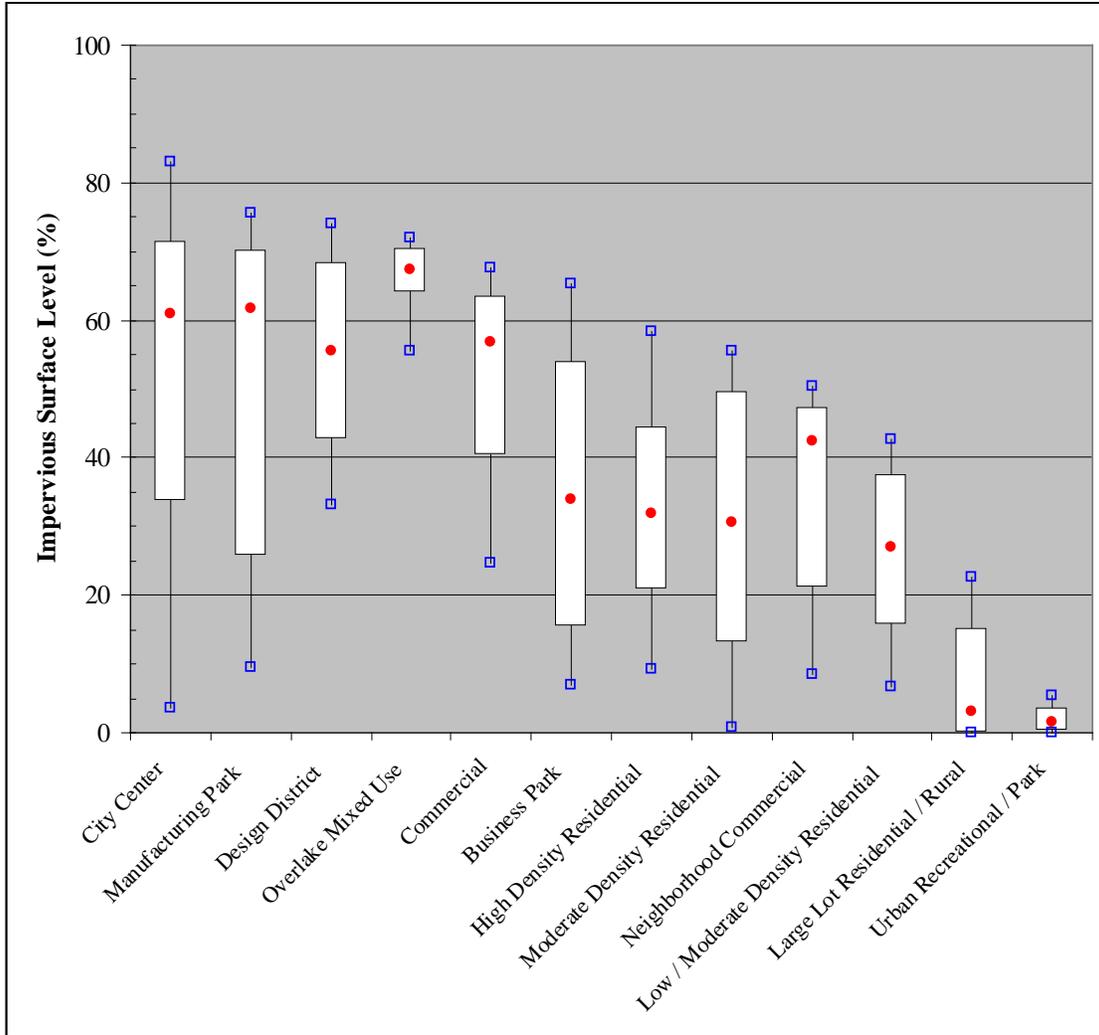


Figure A-16. Box plots of average impervious surface levels observed within polygons specific to each land use type, throughout Redmond. (The upper and lower edges of the central rectangle represent the 75th and 25th percentiles while the central red dot represents the median, or 50th percentile. The projecting upper and lower blue squares represent the 90th and 10th percentiles, respectively.)

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Appendix B: Effective and Total Impervious Surface

A comparison was made between the estimates of impervious surface determined for Redmond's stormwater catchments by Northwest Hydraulics (NHC, 2006) and those by this analysis. Northwest Hydraulics presented impervious surface as effective impervious area (EIA). EIA is defined as impervious surfaces that contribute directly to surface runoff, as opposed to total impervious surface which includes surfaces that may not directly contribute. This analysis applied the total impervious surface measure. Figure B-1 presents the comparison of these two measures of impervious surface.

As observed, though reported differently, estimates of EIA and those determined from grid sampling (total impervious area) are relatively close. In fact, the EIA estimates are, on average, greater by about 16 percent. Ideally, it should be the other way around, because the total impervious surface estimates incorporate areas that may not contribute directly to runoff. Some of the disagreement in the methods may be due to the grid used in this analysis. While the grid is continuous in its definition of impervious surface levels from 20 percent and higher, levels below 20 percent are given values of 0 percent. Catchments with areas having lower impervious surface levels falling into the 0-20 percent range will, depending on its level of representation, reduce the overall average level estimated throughout the catchment. However, despite differing methods and the fairly crude approximations necessary, the two estimates of impervious surface for the catchments are relatively close.

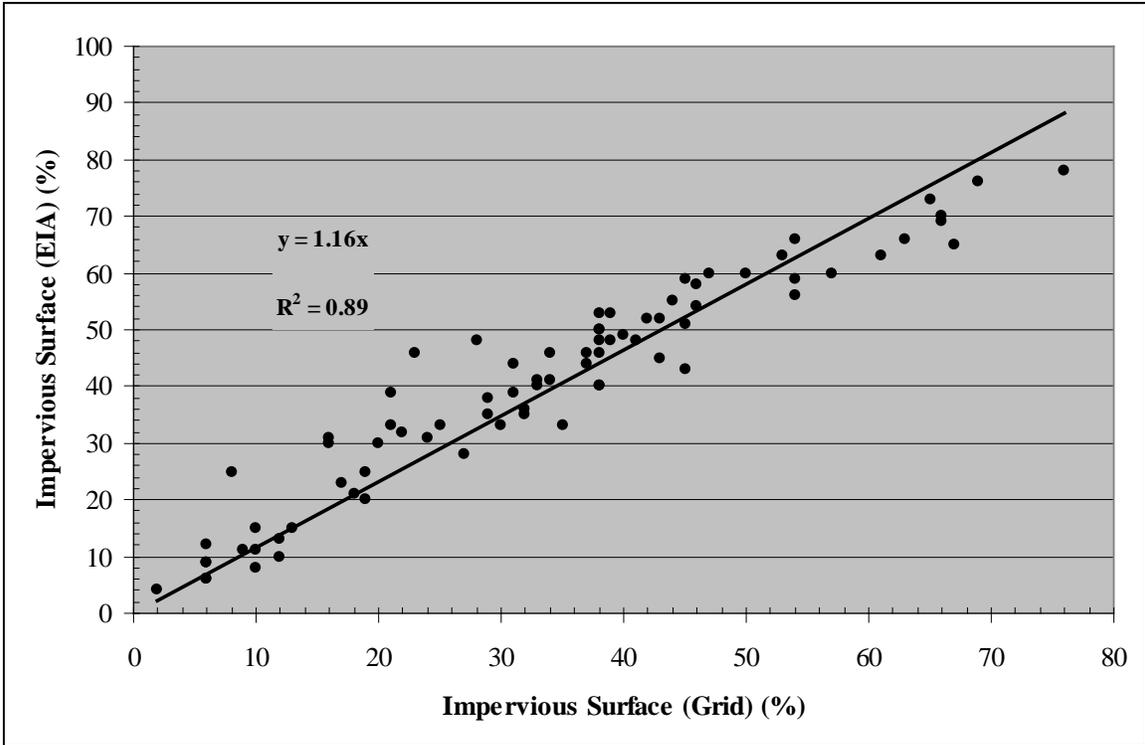


Figure B-1. Comparison between this study's total impervious surface estimates and those reported for effective impervious surface for Redmond's stormwater catchments.

Appendix C: Water Quality Score Data and Figures

Table C-1. Median parameter values for the Redmond water quality monitoring stations.

Monitoring Stations	Flow (cfs)	Conductivity (umhos/cm)	pH	Temperature (C)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	Total Suspended Solids (mg/L)	Fecal Coliform (mpn/100 ml)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)
116th Ditch	0.10	143	7.3	10.8	8.0	3.9	8.3	36	0.037	0.659
46th & W Lk Samm Pkwy	0.37	214	7.9	10.2	10.3	4.5	8.0	525	0.075	0.830
5050 @ W Lk Samm Pkwy	0.53	223	8.0	11.1	10.7	2.4	9.0	365	0.061	0.638
85th St Bridge Upstream		91	7.4	11.1	10.5	3.6	==	==	==	==
85th St Bridge Outfall	0.04	148	7.8	12.6	10.3	4.6	7.5	1000	0.094	1.265
90th Street Bridge Vault	0.10	125	7.5	13.8	8.6	6.2	7.0	285	0.080	0.746
Avondale @ 104th	0.10	134	7.1	12.8	7.2	2.8	15.5	180	0.093	1.515
Avondale @ 116th	0.50	138	7.6	9.3	10.3	3.8	5.3	100	0.049	0.564
Redmond Way @ Bear Creek Upstream	1.25	95	7.4	10.6	10.6	6.1	==	==	==	==
Birdcage @ W Lk Samm Pkwy	0.67	171	7.7	11.6	10.2	3.7	13.5	330	0.061	1.080
Bridlecrest Stream	0.10	191	7.9	11.4	10.5	4.2	7.0	175	0.063	0.744
Idylwood Creek @ W.Lk.Samm.Pkwy	0.27	200	7.8	10.4	10.3	1.7	5.0	290	0.035	0.720
Marymoor Stream	0.30	246	8.1	10.8	10.8	3.7	6.0	210	0.077	0.940
Overlake Sears Trunkline	0.40	76	7.3	13.3	9.4	3.8	17.8	640	0.147	1.520
Perrigo Creek @ Avondale Rd	0.25	183	8.0	10.0	10.8	5.5	5.5	635	0.054	2.580
Peters Creek Main Branch Pond	0.50	204	7.9	10.7	11.1	2.6	==	==	==	==
Peters Creek @ 87th Street	0.33	207	7.8	10.1	10.1	2.4	13.0	330	0.058	1.260
Peters Creek Outfall	1.00	185	7.9	10.6	11.1	3.9	6.3	550	0.054	1.016
Redmond 74 Stream	0.13	166	7.9	10.9	10.1	1.1	==	195	0.055	1.425
Redmond HS Stream @ 116th	0.20	151	7.7	9.8	10.2	1.8	4.5	99	0.044	1.240
RWOWS Vault	0.00	62	6.9	13.5	5.4	10.6	6.5	3600	0.110	1.205
Villa Marina Creek	0.53	206	7.9	12.8	10.2	4.6	12.0	380	0.062	1.480
Willows Creek @ Willows Rd	1.06	183	7.6	9.3	10.7	2.9	6.5	59	0.051	1.160

Table C-2. Maximum parameter values for the Redmond water quality monitoring stations.

Monitoring Stations	Flow (cfs)	Conductivity (umhos/cm)	pH	Temperature (C)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	Total Suspended Solids (mg/L)	Fecal Coliform (mpn/100 ml)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)
116th Ditch	0.25	162	7.7	18.4	11.9	29.8	84.0	750	0.118	1.310
46th & W Lk Samm Pkwy	2.00	240	8.3	16.7	12.8	23.8	58.0	5700	0.295	2.380
5050 @ W Lk Samm Pkwy	3.00	251	8.7	14.7	13.1	22.6	38.0	4000	0.702	1.540
85th St Bridge Upstream		127	7.8	19.9	13.3	32.0	==	==	==	
85th St Bridge Outfall	12.00	==	9.1	19.8	13.1	270.0	36.0	30000	0.540	2.010
90th Street Bridge Vault	4.00	289	9.0	19.5	12.1	101.0	14.0	4300	0.229	1.110
Avondale @ 104th	10.00	285	7.4	18.4	10.7	52.6	26.0	4300	0.220	3.620
Avondale @ 116th	10.00	170	7.8	15.6	13.0	16.0	14.0	5000	0.094	2.300
Redmond Way @ Bear Creek Upstream	==	126	8.0	19.4	13.4	196.0	==	==	==	==
Birdcage @ W Lk Samm Pkwy	5.00	246	8.4	18.2	14.4	12.7	20.0	6300	0.754	2.140
Bridlecrest Stream	0.25	224	8.2	15.1	12.5	76.4	150.0	7000	0.295	3.370
Idylwood Creek @ W.Lk.Samm.Pkwy	7.50	236	8.4	16.0	13.8	120.4	200.0	39000	0.202	1.790
Marymoor Stream	1.50	269	8.4	14.2	12.3	173.0	340.0	3700	0.518	3.060
Overlake Sears Trunkline	8.00	168	8.8	19.1	11.4	155.0	28.0	43000	0.444	3.230
Perrigo Creek @ Avondale Rd	4.00	236	8.3	15.2	13.0	195.0	12.0	2700	0.073	4.260
Peters Creek Main Branch Pond	7.50	250	8.2	16.7	13.1	427.0		==	==	==
Peters Creek @ 87th Street	3.00	251	8.1	16.2	12.6	27.4	20.0	2700	0.149	1.780
Peters Creek Outfall	37.50	237	9.8	18.1	15.8	1080.0	32.0	6500	0.570	1.930
Redmond 74 Stream	1.50	194	8.1	18.0	12.3	58.0	==	1200	0.224	1.700
Redmond HS Stream @ 116th	1.75	190	8.1	17.8	13.5	12.9	10.0	2600	0.125	1.990
RWOWS Vault	1.00	289	7.3	18.0	11.6	64.7	92.0	110000	1.240	4.880
Villa Marina Creek	7.00	257	8.4	17.6	12.4	48.8	42.0	22000	0.232	6.350
Willows Creek @ Willows Rd	3.60	204	8.0	23.0	13.4	236.0	25.0	1200	0.149	3.270

Table C-3. Minimum parameter values for the Redmond water quality monitoring stations.

Monitoring Stations	Flow (cfs)	Conductivity (umhos/cm)	pH	Temperature (C)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	Total Suspended Solids (mg/L)	Fecal Coliform (mpn/100 ml)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)
116th Ditch	0.00	71	7.0	5.0	4.8	1.3	5.0	1	0.014	0.232
46th & W Lk Samm Pkwy	0.00	135	7.2	4.7	7.3	2.0	4.5	1	0.037	0.444
5050 @ W Lk Samm Pkwy	0.07	143	7.3	4.1	4.9	1.1	5.5	1	0.013	0.284
85th St Bridge Upstream	==	77	6.7	4.8	7.0	1.1	==	==	==	==
85th St Bridge Outfall	0.00	20	6.3	4.6	4.0	0.9	5.0	30	0.037	0.725
90th Street Bridge Vault	0.00	67	6.7	6.2	4.4	1.0	5.5	1	0.041	0.290
Avondale @ 104th	0.00	37	6.8	5.4	1.2	1.6	5.0	1	0.031	0.743
Avondale @ 116th	0.07	80	7.1	3.4	7.5	1.2	4.0	27	0.025	0.372
Redmond Way @ Bear Creek Upstream	==	41	3.9	1.4	7.6	0.8	==	==	==	==
Birdcage @ W Lk Samm Pkwy	0.03	108	7.5	4.8	8.2	1.5	7.0	1	0.031	0.536
Bridlecrest Stream	0.02	124	7.3	5.4	7.2	1.1	4.0	1	0.013	0.377
Idylwood Creek @ W.Lk.Samm.Pkwy	0.03	44	7.1	4.7	5.5	0.5	4.0	14	0.020	0.466
Marymoor Stream	0.03	89	7.6	5.9	8.2	2.4	4.0	28	0.050	0.561
Overlake Sears Trunkline	0.00	37	6.6	7.8	6.7	1.1	7.5	1	0.055	1.000
Perrigo Creek @ Avondale Rd	0.01	48	7.3	4.6	8.6	0.0	4.0	26	0.049	2.280
Peters Creek Main Branch Pond	0.13	62	6.9	3.5	9.4	0.5	==	==	==	==
Peters Creek @ 87th Street	0.07	118	7.2	3.7	8.4	1.0	6.0	9	0.036	0.800
Peters Creek Outfall	0.00	6	6.4	2.2	5.1	0.8	4.0	18	0.022	0.556
Redmond 74 Stream	0.07	40	7.2	5.4	8.0	0.1	==	7	0.024	0.889
Redmond HS Stream @ 116 th	0.03	62	7.0	2.3	7.6	0.8	4.0	1	0.013	0.653
RWOWS Vault	0.00	21	5.9	6.6	0.7	2.7	4.0	1	0.031	0.478
Villa Marina Creek	0.03	71	7.2	6.2	9.1	1.0	4.5	1	0.028	0.914
Willows Creek @ Willows Rd	0.07	89	7.2	3.2	5.5	1.0	1.0	2	0.033	0.913

Table C-4. Sample number by parameter and monitoring station.

Monitoring Stations	Flow (cfs)	Conductivity (umhos/cm)	pH	Temperature (C)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	Total Suspended Solids (mg/L)	Fecal Coliform (mpn/100 ml)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)
116th Ditch	18	20	23	23	23	23	6	22	23	9
46th & W Lk Samm Pkwy	24	21	24	24	24	24	7	24	24	12
5050 @ W Lk Samm Pkwy	24	21	24	24	24	24	5	24	24	11
85th St Bridge Upstream	==	91	87	91	91	90	==	==	==	==
85th St Bridge Outfall	100	107	104	108	108	107	6	16	18	8
90th Street Bridge Vault	19	21	24	24	24	24	5	24	24	11
Avondale @ 104th	21	21	24	24	24	24	2	23	24	12
Avondale @ 116th	27	24	27	27	27	27	6	26	27	11
Redmond Way @ Bear Creek Upstream	2	76	72	76	76	76	==	==	==	==
Birdcage @ W Lk Samm Pkwy	22	20	24	24	24	24	2	23	23	12
Bridlecrest Stream	24	21	24	24	24	23	10	24	24	11
Idylwood Creek @ W.Lk.Samm.Pkwy	55	55	58	58	58	58	13	27	27	13
Marymoor Stream	27	24	27	27	27	27	11	27	27	14
Overlake Sears Trunkline	23	21	24	24	24	24	2	24	24	==
Perrigo Creek @ Avondale Rd	92	99	95	99	99	97	4	6	6	5
Peters Creek Main Branch Pond	73	73	69	73	73	72	==	==	==	==
Peters Creek @ 87th Street	24	21	24	24	24	24	2	24	24	11
Peters Creek Outfall	150	158	157	160	160	160	33	27	27	14
Redmond 74 Stream	19	18	19	19	19	19	==	18	19	6
Redmond HS Stream @ 116th	25	24	27	27	27	27	3	27	27	13
RWOWS Vault	20	24	25	26	26	26	8	22	26	12
Villa Marina Creek	21	20	23	23	23	23	3	24	24	12
Willows Creek @ Willows Rd	91	89	92	92	92	91	44	27	27	14

Station Name	Station Number
116th Ditch	1
46th & W Lk Samm Pkwy	2
5050 @ W Lk Samm Pkwy	3
85th St Bridge Outfall	4
Avondale @ 104th	5
Avondale @ 116th	6
Birdcage @ W Lk Samm Pkwy	7
Bridlecrest Stream	8
Idylwood Creek @ W.Lk.Samm.Pkwy	9
Marymoor Stream	10
Perrigo Creek @ Avondale Rd	11
Peters Creek @ 87th Street	12
Peters Creek Outfall	13
Redmond 74 Stream	14
Redmond HS Stream @ 116th	15
Villa Marina Creek	16
Willows Creek @ Willows Rd	17

Table C-5. Water quality score generation.

Station ¹ No.	Max Temp	Temp Score	Station No.	Min Do	DO Score	Station No.	Max pH	pH Score	Station No.	Median Turbidity	Turbidity Score	Station No.	Median FC	FC Score	Station No.	Median TP	TP Score	Station No.	Median TN	TN Score
10	14.2	-8.00	16	9.1	-8.00	5	7.4	-8	14	1.1	-8	1	36	-8	9	0.035	-8	6	0.564	-8
3	14.7	-7.00	11	8.6	-7.00	1	7.7	-7	9	1.7	-7	17	59	-7	1	0.037	-7	3	0.638	-7
8	15.1	-6.00	12	8.4	-6.00	6	7.8	-6	15	1.8	-6	15	99	-6	15	0.044	-6	1	0.659	-6
11	15.2	-5.00	10	8.2	-4.50	17	8.0	-5	3	2.4	-4.5	6	100	-5	6	0.049	-5	9	0.720	-5
6	15.6	-4.00	7	8.2	-4.50	15	8.1	-3	12	2.4	-4.5	8	175	-4	17	0.051	-4	8	0.744	-4
9	16.0	-3.00	14	8.0	-3.00	12	8.1	-3	5	2.8	-3	5	180	-3	11	0.054	-2.5	2	0.830	-3
12	16.2	-2.00	15	7.6	-2.00	14	8.1	-3	17	2.9	-2	14	195	-2	13	0.054	-2.5	10	0.940	-2
2	16.7	-1.00	6	7.5	-1.00	8	8.2	-1	4	3.6	-1	10	210	-1	14	0.055	-1	13	1.016	-1
16	17.6	0.00	2	7.3	0.00	11	8.3	0	10	3.7	0	9	290	0	12	0.058	0	7	1.080	0
15	17.8	1.00	8	7.2	1.00	2	8.3	0	7	3.7	0	7	330	1.5	7	0.061	1.5	17	1.160	1
14	18.0	2.00	17	5.5	2.50	9	8.4	2.5	6	3.8	1	12	330	1.5	3	0.061	1.5	15	1.240	2
13	18.1	3.00	9	5.5	2.50	7	8.4	2.5	13	3.9	2.5	3	365	3	16	0.062	3	12	1.260	3
7	18.2	4.00	13	5.1	4.00	10	8.4	2.5	1	3.9	2.5	16	380	4	8	0.063	4	4	1.265	4
1	18.4	5.50	3	4.9	5.00	16	8.4	2.5	8	4.2	4	2	525	5	2	0.075	5	14	1.425	5
5	18.4	5.50	1	4.8	6.00	3	8.7	5	2	4.5	5	13	550	6	10	0.077	6	16	1.480	6
4	19.8	7.00	4	4.0	7.00	4	9.1	6	16	4.6	6	11	635	7	5	0.093	7	5	1.515	7
17	23.0	8.00	5	1.2	8.00	13	9.8	7	11	5.5	7	4	1000	8	4	0.094	8	11	2.580	8
Overall Median	17.6			7.3			8.3			3.7			290			0.580			1.080	

1. Refer to top table for station name.

Table C-6. Water quality scores sorted by station name.

Station Name	Station No.	Max Temp	Temp Score	Min Do	DO Score	Max pH	pH Score	Median Turbidity	Turbidity Score	Median FC	FC Score	Median TP	TP Score	Median TN	TN Score	Overall Score
116th Ditch	1	18.4	5.50	4.8	6.00	7.7	-7	3.9	2.5	36	-8	0.037	-7	0.659	-6	-14.00
46th & W Lk Samm Pkwy	2	16.7	-1.00	7.3	0.00	8.3	0	4.5	5	525	5	0.075	5	0.830	-3	11.00
5050 @ W Lk Samm Pkwy	3	14.7	-7.00	4.9	5.00	8.7	5	2.4	-4.5	365	3	0.061	1.5	0.638	-7	-4.00
85th St Bridge Outfall	4	19.8	7.00	4.0	7.00	9.1	6	3.6	-1	1000	8	0.094	8	1.265	4	39.00
Avondale @ 104th	5	18.4	5.50	1.2	8.00	7.4	-8	2.8	-3	180	-3	0.093	7	1.515	7	13.50
Avondale @ 116th	6	15.6	-4.00	7.5	-1.00	7.8	-6	3.8	1	100	-5	0.049	-5	0.564	-8	-28.00
Birdcage @ W Lk Samm Pkwy	7	18.2	4.00	8.2	-4.50	8.4	2.5	3.7	0	330	1.5	0.061	1.5	1.080	0	5.00
Bridlecrest Stream	8	15.1	-6.00	7.2	1.00	8.2	-1	4.2	4	175	-4	0.063	4	0.744	-4	-6.00
Idylwood Creek @ W.Lk.Samm.Pkwy	9	16.0	-3.00	5.5	2.50	8.4	2.5	1.7	-7	290	0	0.035	-8	0.720	-5	-18.00
Marymoor Stream	10	14.2	-8.00	8.2	-4.50	8.4	2.5	3.7	0	210	-1	0.077	6	0.940	-2	-7.00
Perrigo Creek @ Avondale Rd	11	15.2	-5.00	8.6	-7.00	8.3	0	5.5	7	635	7	0.054	-2.5	2.580	8	7.50
Peters Creek @ 87th Street	12	16.2	-2.00	8.4	-6.00	8.1	-3	2.4	-4.5	330	1.5	0.058	0	1.260	3	-11.00
Peters Creek Outfall	13	18.1	3.00	5.1	4.00	9.8	7	3.9	2.5	550	6	0.054	-2.5	1.016	-1	19.00
Redmond 74 Stream	14	18.0	2.00	8.0	-3.00	8.1	-3	1.1	-8	195	-2	0.055	-1	1.425	5	-10.00
Redmond HS Stream @ 116th	15	17.8	1.00	7.6	-2.00	8.1	-3	1.8	-6	99	-6	0.044	-6	1.240	2	-20.00
Villa Marina Creek	16	17.6	0.00	9.1	-8.00	8.4	2.5	4.6	6	380	4	0.062	3	1.480	6	13.50
Willows Creek @ Willows Rd	17	23.0	8.00	5.5	2.50	8.0	-5	2.9	-2	59	-7	0.051	-4	1.160	1	-6.50

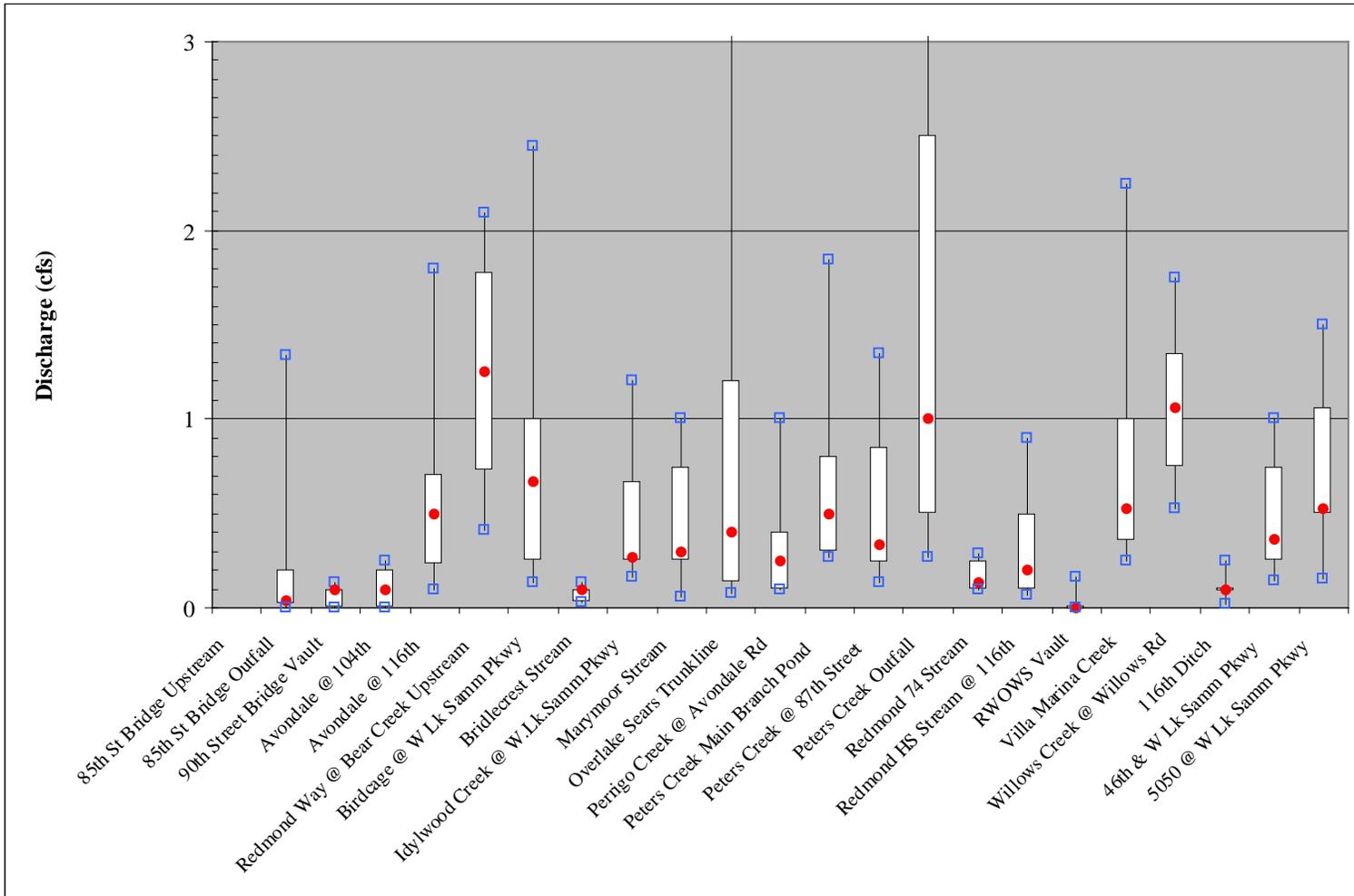


Figure C-1. Box plots of discharge (cubic feet per second) observed for Redmond stations.

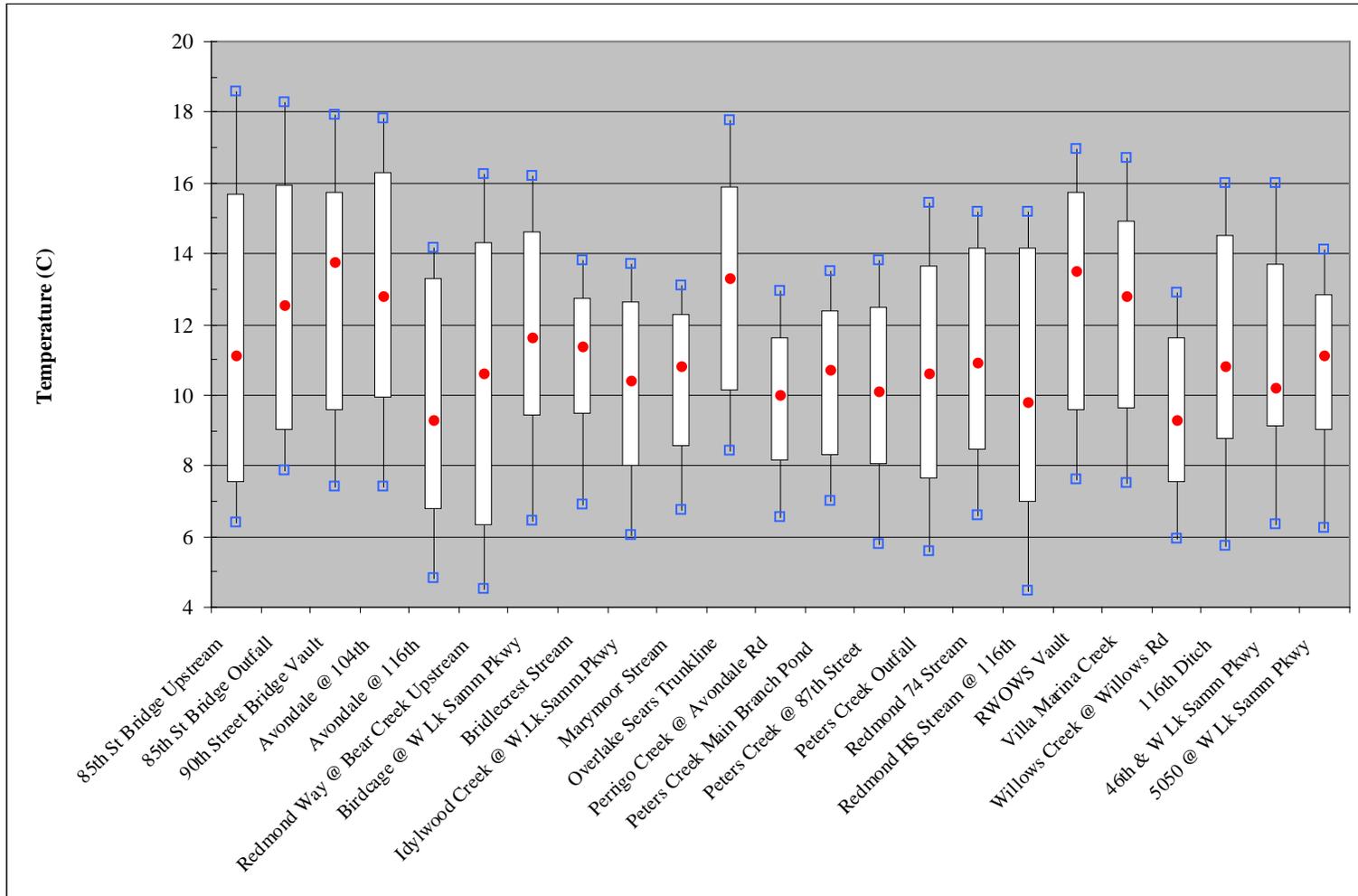


Figure C-2. Box plots of temperature (C) observed for Redmond stations.

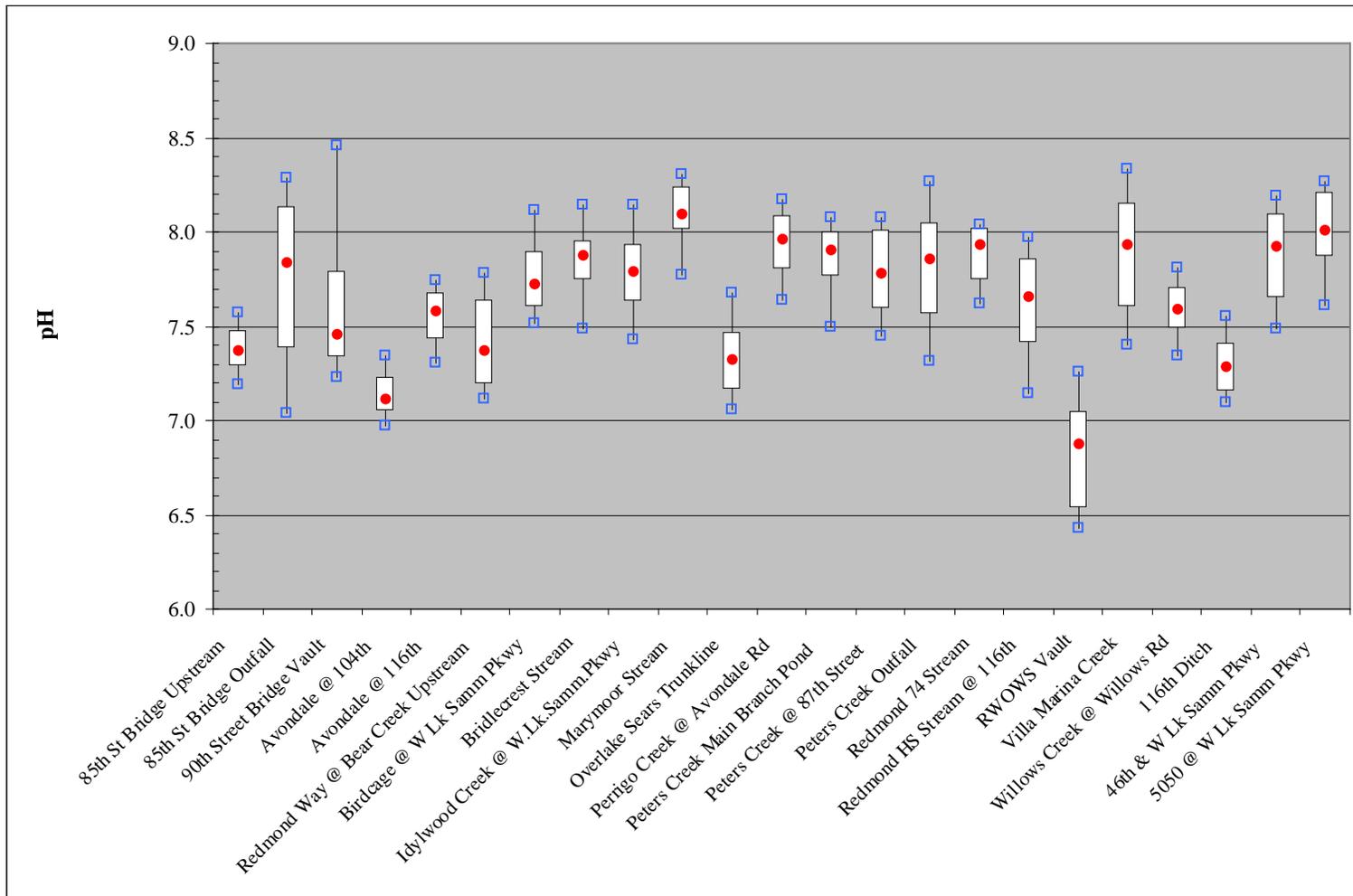


Figure C-3. Box plots of pH observed for Redmond stations.

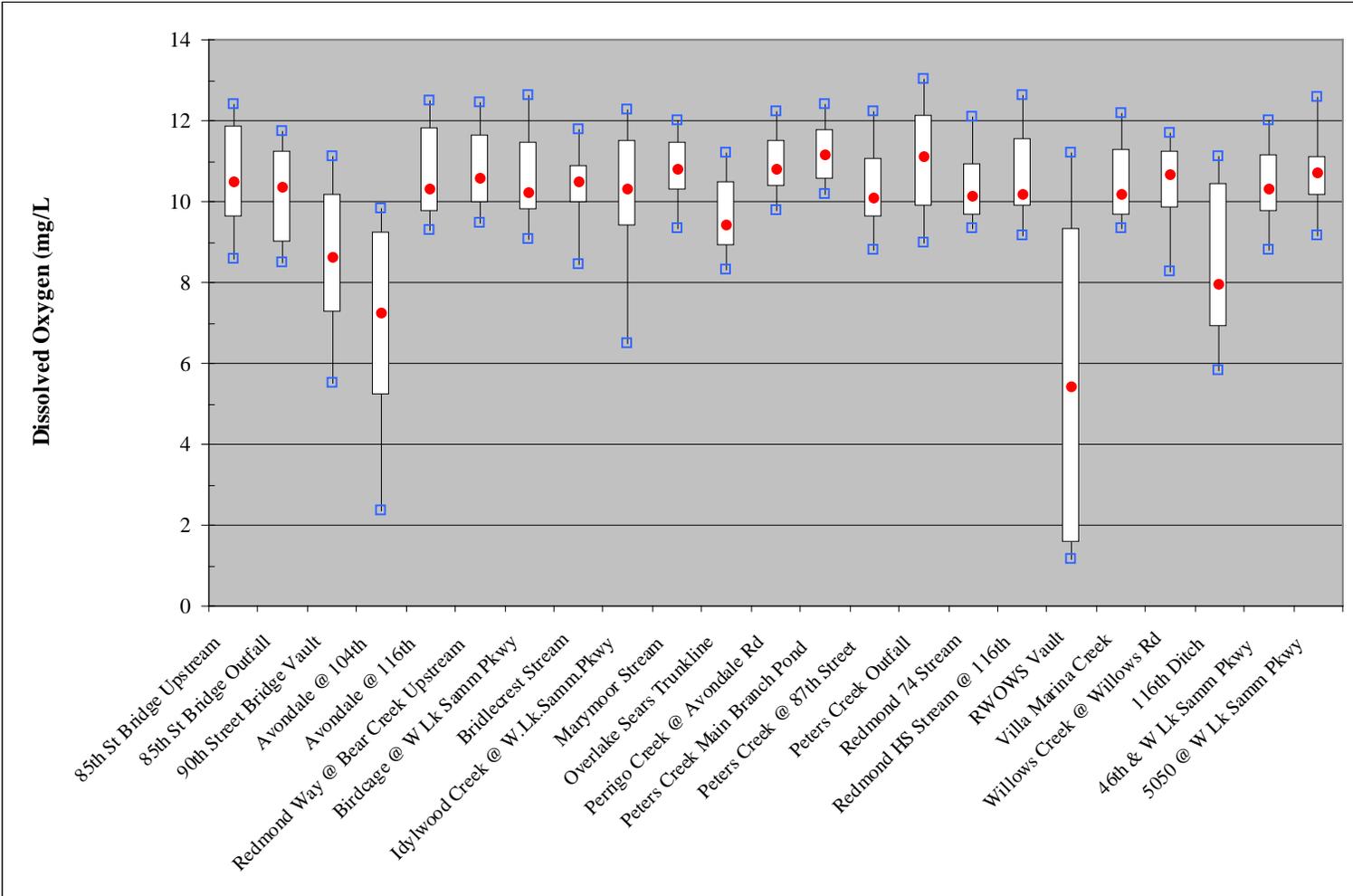


Figure C-4. Box plots of dissolved oxygen levels (mg/L) observed for Redmond stations.

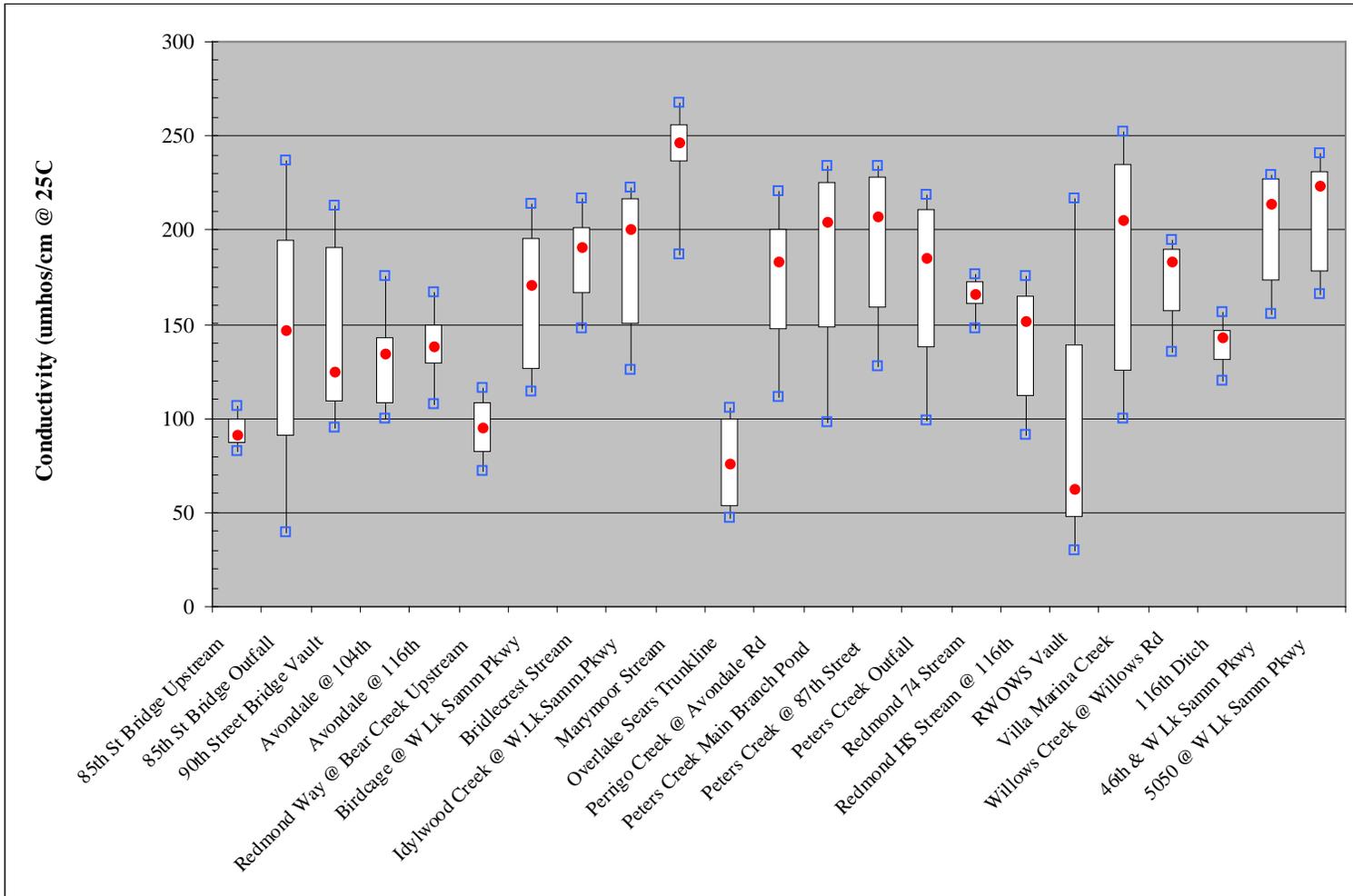


Figure C-5. Box plots of conductivity levels (umhos/cm) observed for Redmond stations.

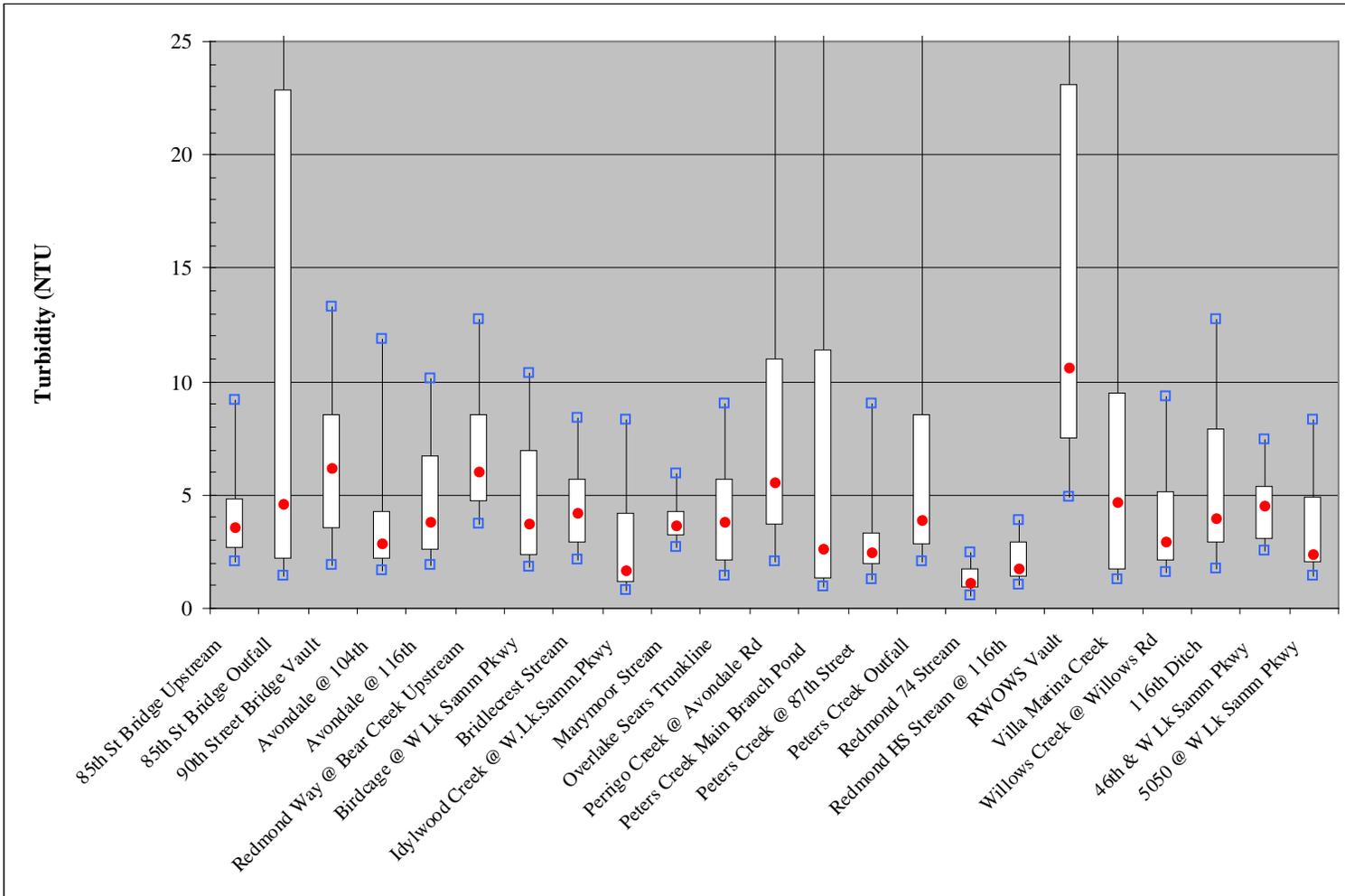


Figure C-6. Box plots of turbidity levels (NTU) observed for Redmond stations.

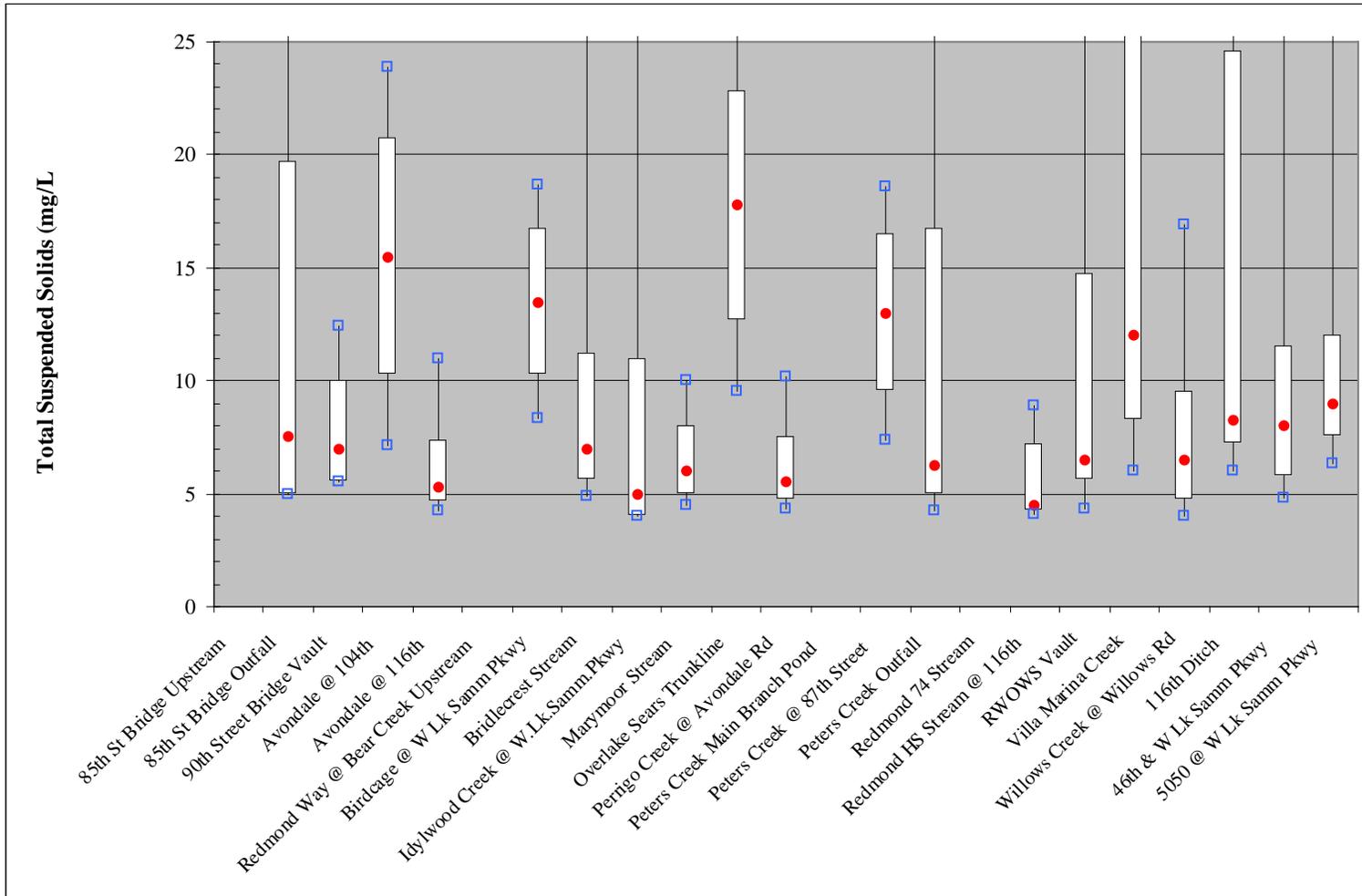


Figure C-7. Box plots of total suspended solids levels (mg/L) observed for Redmond stations.

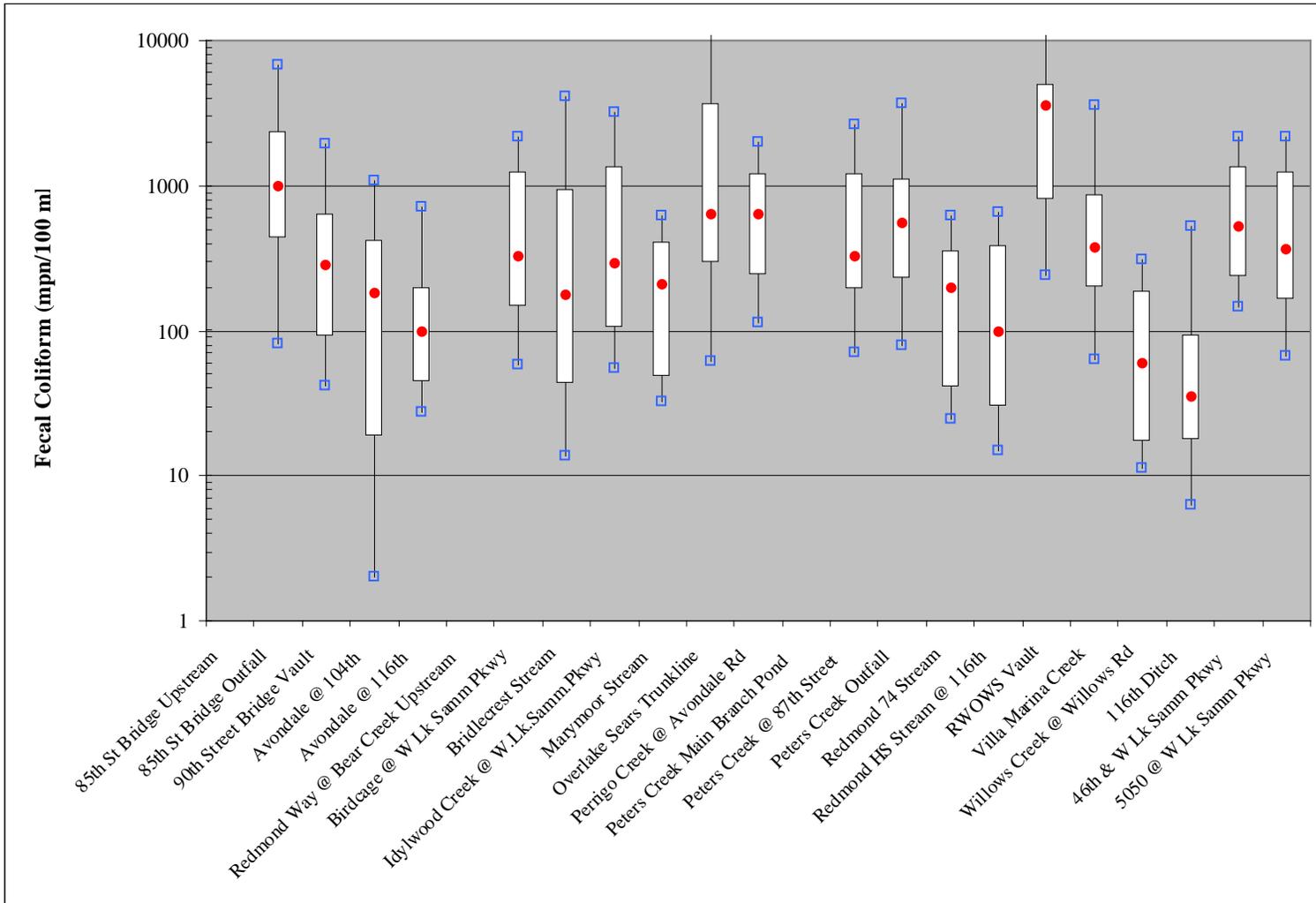


Figure C-8. Box plots of fecal coliform bacteria levels (mpn/100 ml) observed for Redmond stations.

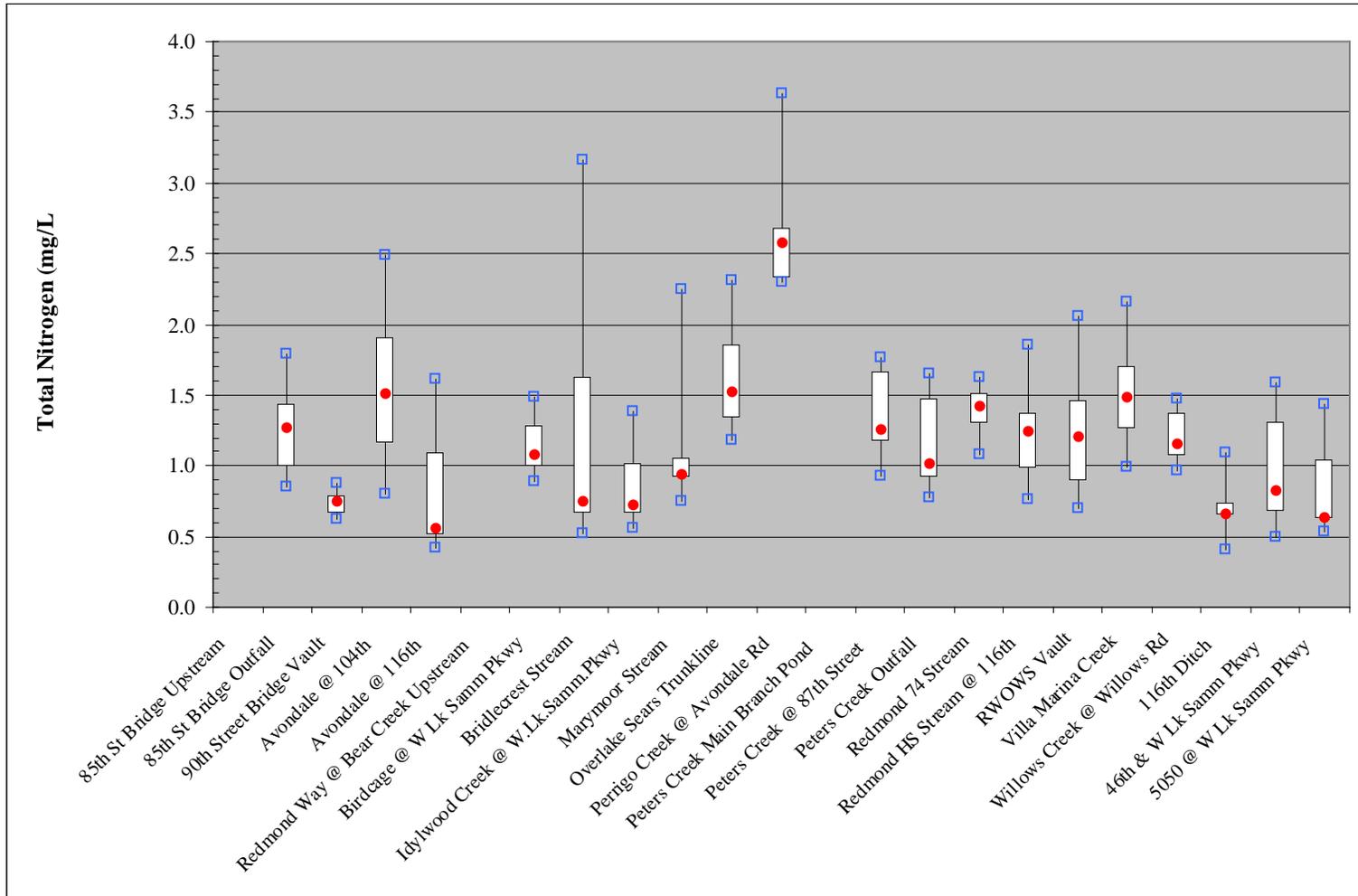


Figure C-9. Box plots of total nitrogen levels (mg/L) observed for Redmond stations.

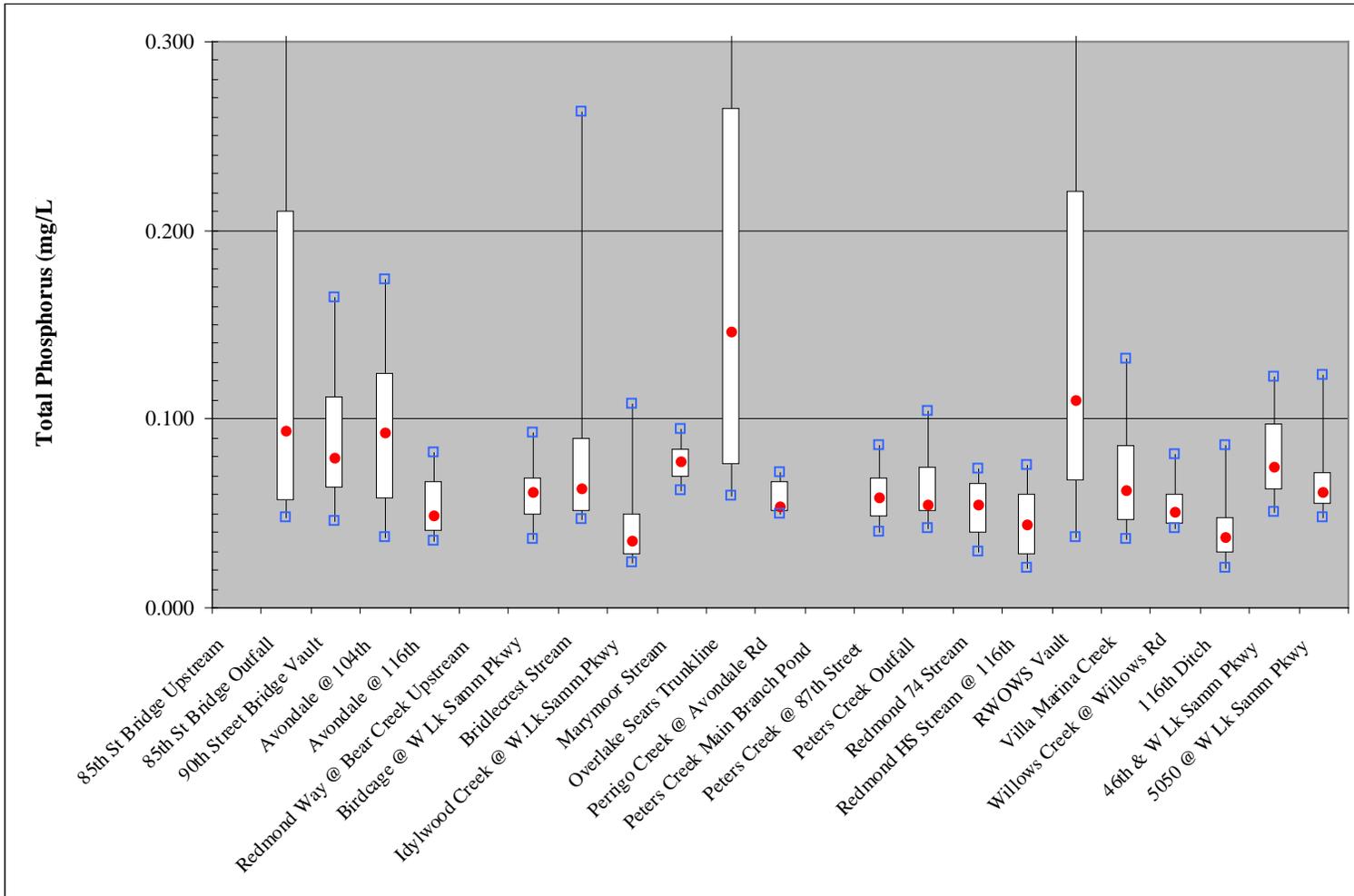


Figure C-10. Box plots of total phosphorus levels (mg/L) observed for Redmond stations.