# Geomorphology and Hydrology Assessment
# for
# Mill Creek

by

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# 1 Purpose

A geomorphology and hydrology assessment was conducted for Mill Creek to help understand the dynamic processes at work within the basin and their interrelation with human influences. The assessment provides insights into the mechanisms that create real or perceived watershed and stream corridor impairments. Additionally, the assessment provides an understanding of how basin physical conditions and processes influence current and potential future hydrology, channel morphology, flooding, channel erosion, water quality and fish and wildlife habitat. Results of the assessment were used to form management recommendations and identify future capital stormwater and habitat restoration projects.

# 2 Methods

## 2.1 Watershed Conditions

Available data and documentation regarding watershed conditions were collected, including: historic and current aerial photography; soils data; geologic maps and reports; topographic data; land cover and land use data; stormwater infrastructure data; existing hydraulic models and floodplain mapping; feature inventory data; and available technical reports. A field reconnaissance was conducted on April 8 and April 11, 2008 to observe current conditions with regard to channel form, stream stability, riparian vegetation, channel bed and bank material, woody debris, surrounding land use, hydraulic structures, sinuosity, hydromodifications and floodplain connectivity. The field observations are summarized in Appendix A. Field photographs are hyperlinked in the provided ArcGIS project file (SNAP_StudyArea_Basins.mxd).

The available data and documentation were reviewed and evaluated in combination with field observations to characterize the existing basin physical conditions and provide insight into the physical processes and human influences that are the controlling factors on the hydrology and geomorphology of Mill Creek. The details of this effort are presented in Section 3.1.

## 2.2 Hydrology

The Mill Creek basin and tributary basin areas were delineated using the provided topographic data. Available hydrologic data from the stream flow gage near the mouth of Mill Creek were collected and evaluated. The period of record for the gage is from 5/20/2003 to present. The available record is too short to conduct peak or low flow frequency analyses. However, a recently updated HSPF hydrologic model (WEST, 2008) is available for the Mill Creek basin. Peak flow statistics were developed from the HSPF model output. Low flow conditions were characterized based on the available data and model output. A quantitative indicator of the flashiness of a basin is the value of $T_{Qmean}$, which is the portion of time mean daily flows exceed the mean annual flow. $T_{Qmean}$ was determined using the available flow data from the stream gage for water years 2003-2007. $T_{Qmean}$ was also determined from the available HSPF model output data for the existing and future conditions.

## 2.3 Geomorphology

The morphologic characteristics for Mill Creek were described. This effort included evaluation of channel planform, channel profile, and valley geometry. Channel planform was characterized using current aerial photography supplemented with LiDAR derived stream centerlines (Clark County, 2004). Channel profiles were created using data from the updated HEC-RAS model for Mill Creek (WEST, 2008). Valley cross sections were located along the Mill Creek and tributary valleys. Cross section spacing was selected to best represent the variations in valley form and how the form transitions from upstream to downstream. Elevation data for each cross section were extracted from the digital terrain model (DTM) of the basin and aligned along a common central axis for plotting purposes. The DTM was developed from the available 2-foot contour interval topographic mapping (Clark County, 2003).

Incipient motion particle size characteristics for Mill Creek were estimated from HEC-RAS hydraulic model output data for a range of flow conditions. The incipient motion particle sizes were compared to the bed material size characteristics for Mill Creek to understand the flow conditions that are necessary for bed material transport.

In addition to the evaluation of morphologic characteristics of the channels, a discussion regarding the role of large woody debris in channel development is provided.

# 3 Results

## 3.1 Watershed Conditions

### 3.1.1 Geology

Mill Creek is a 11.9 square mile drainage basin located within the Battle Ground (USGS, 1990), Ridgefield (1990) and Orchards (USGS, 1990) Quadrangles, which are located in the northern part of the Portland Basin, a roughly 770 square mile topographic and structural depression in the central Puget-Willamette Lowland (Beeson et al, 1989; Swanson et al, 1993; Yeats et al, 1996; Evarts, 2004). The Portland Basin is approximately 40 miles long and 20 miles wide, with its long axis oriented northwest (Evarts, 2004). Previous studies (L.M. Liberty, 2003; Swanson et al, 1993; Mabey and Madin, 1995) indicate that as much as 1,800 feet of late Miocene and younger sediments have accumulated in the deepest part of the basin near Vancouver. Most of the basin-fill material was carried in from the east by the Columbia River (Evarts, 2004) which flows westward just south of the Mill Creek basin. A geologic map of the Mill Creek basin is shown in Figure 1.

The physiography of the Mill Creek basin is dominantly a nearly flat surface of elevation 200 to 300 feet developed on the basin-fill sediments. The ground surface of the western portion of the basin displays elongated ridges and troughs (fluting) that trend in a north-south orientation. These are thought to be bed forms that were created by the Missoula Floods (Howard, 2002). A broad north-south trending valley named Manor Trough is located in the middle portion of the basin. The multiple-fluted Manor Trough mostly lacks (Pleistocene) fine-sand deposits and therefore records catastrophic-flood erosion into older Upper Troutdale Formation gravels along a major historic flood channel (Howard, 2002).

The geologic formation that forms much of the surface of the Mill Creek basin is the Pleistocene Alluvium resulting from deposition of cataclysmic flood deposits of clay, silt, and fine to medium sand. Late in the last glacial period, a series of glacial outburst floods from Glacial Lake Missoula flowed down the Columbia River valley and ponded in the Portland Basin. This resulted in deposition of silt and fine sand sediments as much as 100 feet thick (Waitt, 1994, 1996; Evarts, 2004).

Underlying the Cataclysmic Flood Deposits is Pleistocene or late Pliocene age conglomerate beds of sand, gravel and cobble. Howard (2002) interpreted these deposits to be an alluvial fan member of the Upper Troutdale Formation. The conglomerate consists principally of clasts derived from the Skamania Volcanics with only minor amounts of Columbia River derived material. Paleocurrent directions are to the southwest, consistent with an alluvial fan origin from the Cascade Range foothills. As seen in Figure 1, the Alluvial Fan Member of the Upper Troutdale Formation is exposed along the central portions of the Mill Creek basin. The Upper Troutdale Formation is also exposed along the lower portion of the basin; however, unlike the exposures in the central portion of the basin, it consists mostly of ancestral Columbia River sediments (personal communication with Rod Swanson, 2008). There is also a significant domed exposure of this member in the eastern portion of the basin near NE 87th Avenue. Water wells on and near the dome suggest that the surface of the underlying fine-grained Troutdale formation is also domed. Although not penetrated by the water wells, an underlying intrusion of Boring Lava is thought to have created the dome (Howard, 2002).

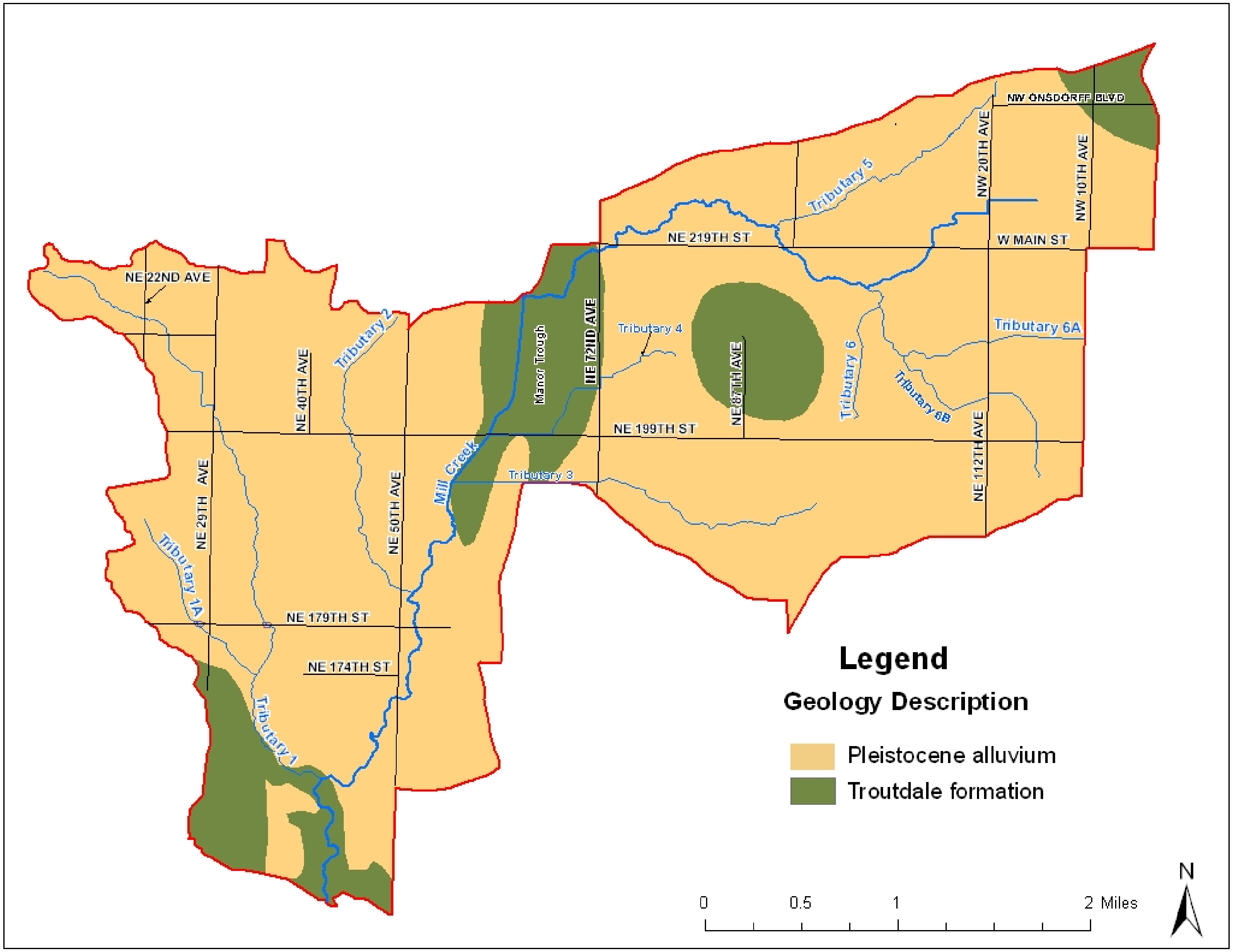


**Figure 1. Geologic Map of the Mill Creek basin (data from DNR Open File Report #87-10; Howard, 2002; and Evarts, 2004).**

### 3.1.2 Streams

A map showing the boundaries of the Mill Creek basin is shown in Figure 2. The 11.9 square mile drainage basin is approximately 5 miles wide from east to west and 4 miles long from north to south. Mill Creek is a 3rd order tributary to Salmon Creek and is approximately 8 miles in length. The headwaters are located in the northeastern most portion of the basin near NW 10th Avenue (SR 503 in the City of Battleground. From its headwaters, the stream flows west crossing under NE 219th Street (SR 502) three times. About 0.25 miles downstream of NE 72nd Avenue, Mill Creek intersects a north-south aligned channel. The channel flowing north drains to the East Fork Lewis River. The channel flowing south is the continuation of the mainstem of Mill Creek which heads in a south-southwest direction to its confluence with Salmon Creek. Major tributaries to Mill Creek are unnamed. Therefore, for discussion purposes they were given the following names: Tributary 1, Tributary 1A, Tributary 2, Tributary 3, Tributary 4, Tributary 5, Tributary 6, Tributary 6A, and Tributary 6B. Tributaries 1, 1A and 2 drain the western portion of the basin and generally flow from north to south. Tributaries 3 and 4 drain the central portion of the basin and generally flow from east to west. Tributary 5 drains the northeastern portion of the basin and generally flows from northeast to southwest. Tributaries 6, 6A and 6B drain the southeastern portion of the basin and generally flow from southeast to northwest.

The majority of tributary stream channels in the basin have bed and bank material consisting of clay-, silt-, and sand-sized sediment owing to the fine grained nature of the Cataclysmic Flood Deposits that formed the parent bedrock and soils that cover the a significant portion of the basin. Several reaches of Mill Creek have bed material consisting of gravel and cobble that originates from the underlying exposures of Upper Troutdale Formation.

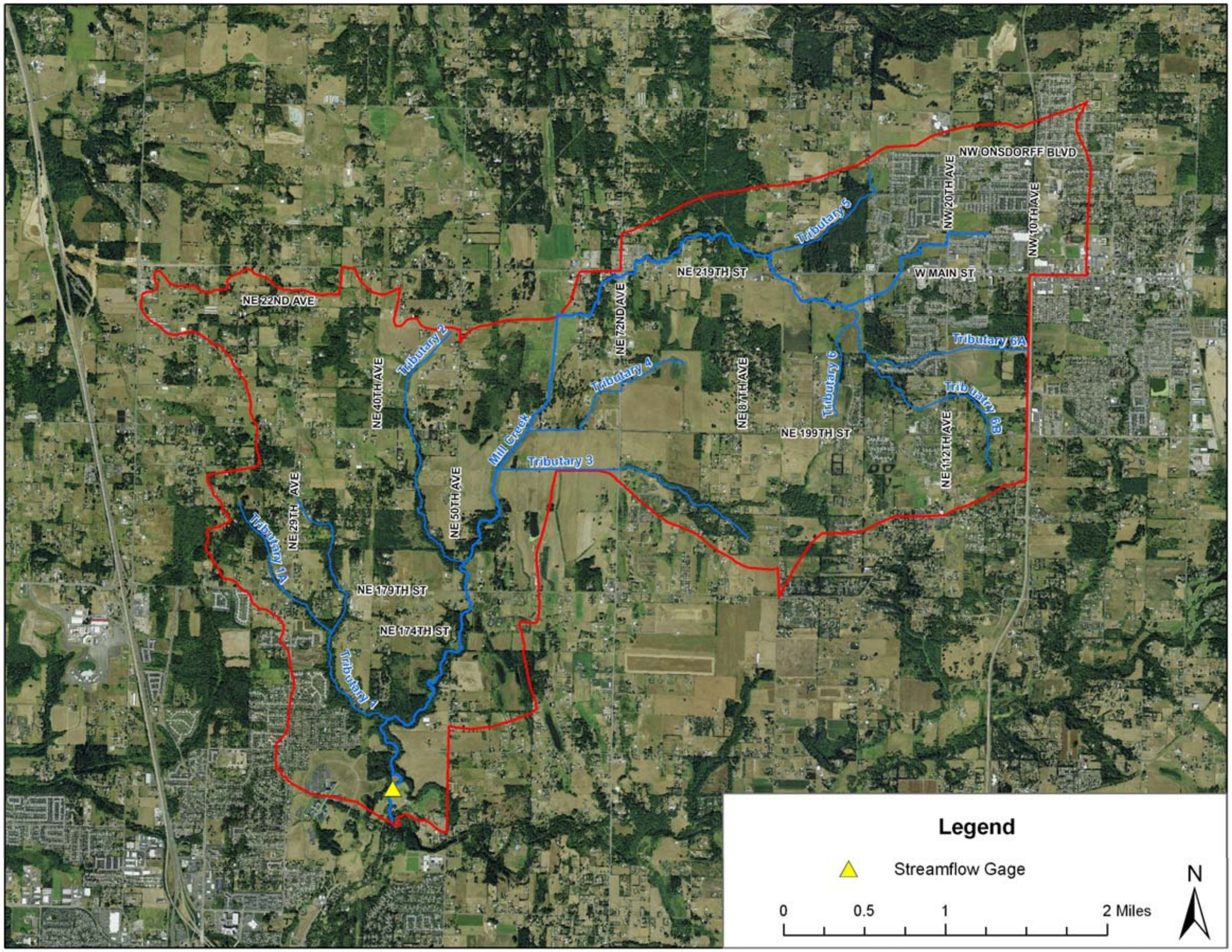


**Figure 2. Mill Creek drainage basin map.**

### 3.1.3 Soils

Mill Creek basin soils are primarily in Hydrologic Soil Group C which comprises 57.3% of basin area. The remaining soils are in Group B, 13.4% and Group D, 29.2% of basin area. An NRCS hydrologic soil group map is shown in Figure 3. As seen in the figure, the majority of Mill Creek is located within the Group C soils.

Mapped soil units in the Mill Creek basin are summarized in Table 1. An NRCS soil map is shown in Figure 4. Watershed soils generally consist of clay, silt and sand sized material derived from the underlying Cataclysmic Flood Deposits. These fine soils are the source materials that are supplied to the stream channels as a result of surface erosion.

**Table 1. Mapped soil units in the Mill Creek basin**

| Soil Unit | Percentage of Basin |
|---|---|
| Dollar loam | 28.3 |
| Gee silt loam | 23.0 |
| Hesson clay loam | 4.7 |
| Hillsboro loam | 2.8 |
| Cove silty clay loam | 5.1 |
| Hillsboro silt loam | 8.8 |
| Hockinson loam | 14.8 |
| Hockinson-Dollar loams | 4.4 |
| Lauren loam | 0.7 |
| McBee silt loam | 0.1 |
| McBee silty clay loam | 0.1 |
| Odne silt loam | 3.7 |
| Olequa silt loam | 0.1 |
| Olequa silty clay loam | 0.8 |
| Puyallup fine sandy loam | 0.2 |
| Sara silt loam | 0.6 |
| Semiahmoo muck | 0.6 |
| Tisch silt loam | 0.4 |
| Washougal gravelly loam | 0.7 |

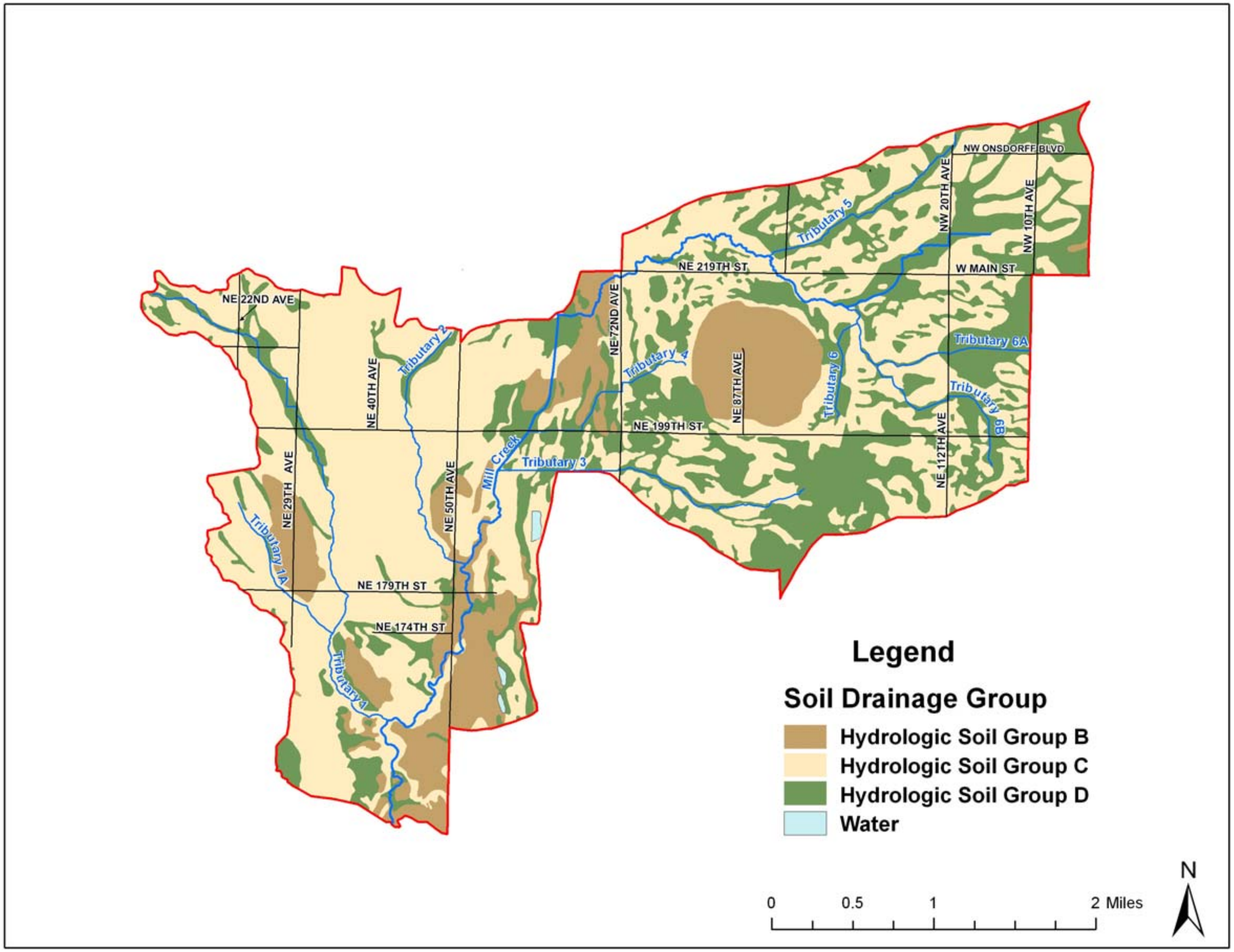


**Figure 3. Hydrologic soil group classification of soils in Mill Creek Basin (data from NRCS, 2004).**

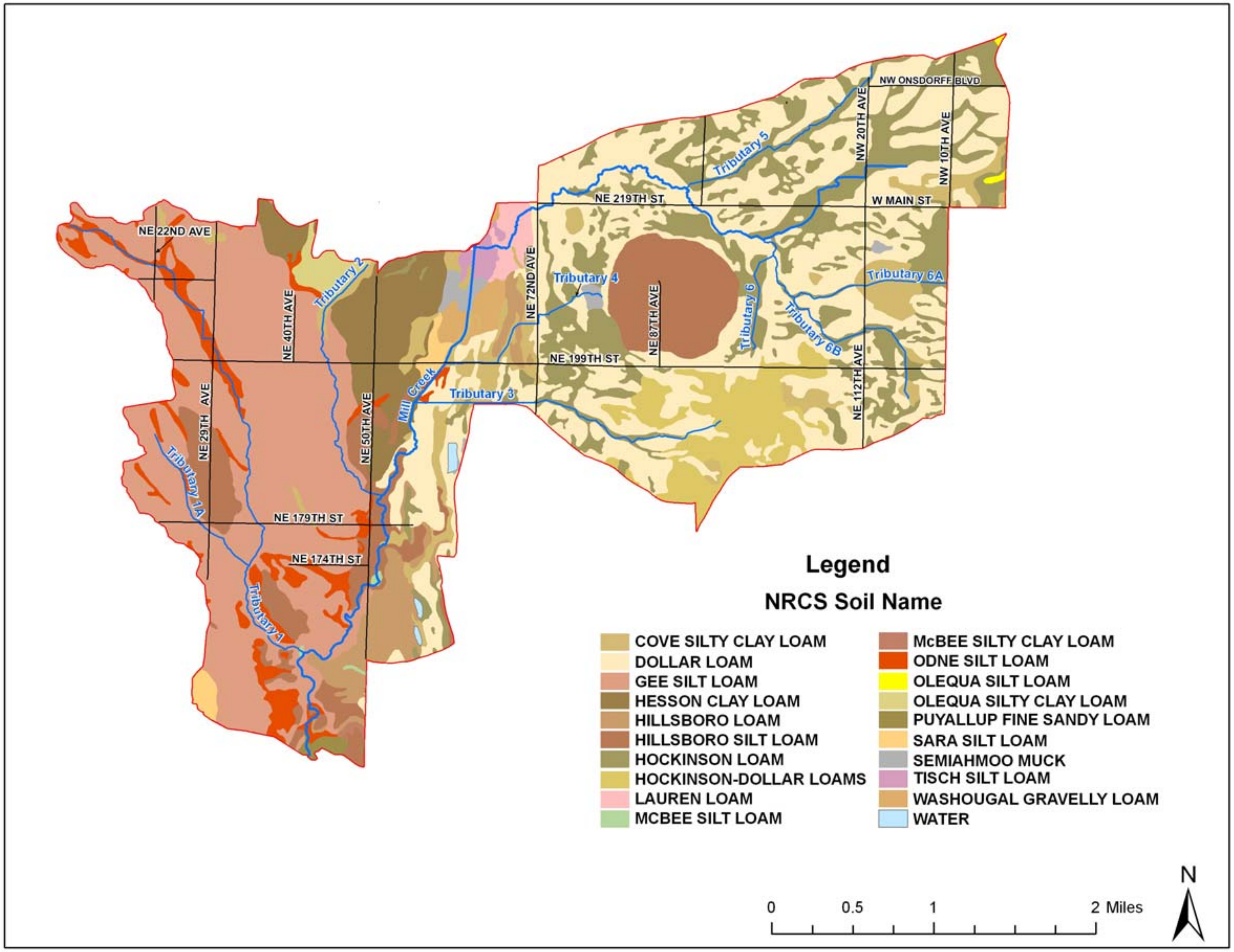


**Figure 4. Soils map for the Mill Creek Basin (data from NRCS, 2004).**

### 3.1.4 Topography

The topography of Mill Creek basin is characterized by nearly flat, slightly dissected surfaces with a broad shallow valley (Manor Trough) oriented in an approximately north-south alignment. Elevations range from approximately 450 feet at the southwestern edge of the basin to approximately 130 feet at the confluence with Salmon Creek at the southern edge of the basin. A prominent topographic feature in the basin is the large domed hill that is approximately 400 feet in elevation located north of 199th Street near NE 87th Avenue. The average basin elevation is 258 feet and the average watershed slope is 4.2 percent (Wierenga, 2005). Floodplain terraces are generally narrow or nonexistent in the upper portion of the basin. Approximately 0.25 miles downstream of NE 72nd Avenue, Mill Creek enters a very broad valley (Manor Trough) where the floodplain terrace expands to nearly 1,500 feet in width and extends nearly 1.5 miles southward to NE 179th Street. At this location Mill Creek enters a more confined valley with floodplain terraces that range between 200 and 300 feet in width. Moderately steep slopes (erosional scarps) occur adjacent to the floodplain terraces and generally increase in height in the downstream direction. The erosional scarps likely developed from incision and lateral migration of Mill Creek into the Cataclysmic Flood Deposits and underlying Upper Troutdale Formation. A shaded topographic relief map of the basin that illustrates the general extent of floodplain terraces is shown in Figure 5.

### 3.1.5 Disturbances

There is little documentation available regarding significant historic disturbances in the Mill Creek basin. Forest fires and flooding were likely the main disturbances prior to Euro-American settlement. Since much of the forest land was converted to agricultural uses in the early 20th century, forest fires have likely not been a significant source of disturbance in the basin since that time. Historic flooding along Mill Creek is not well documented; however, records of flooding along other streams in Clark County suggest that significant flooding occurred in 1964, 1977, and 1996. As described in Section 3.2.2.1, moderate flooding occurred in December 2007. Flooding continues to provide periodic disturbance and may likely have increased in severity as the basin land cover was converted from forest to agriculture and more recently from agriculture to a mix of agriculture, urban housing and commercial development. Future flooding conditions are likely to be exacerbated by future increases in impervious surface area. Significant human-caused disturbance in the basin includes land cover and land use changes and the creation of drainage channels. Details of these disturbances are described in Section 3.1.6.

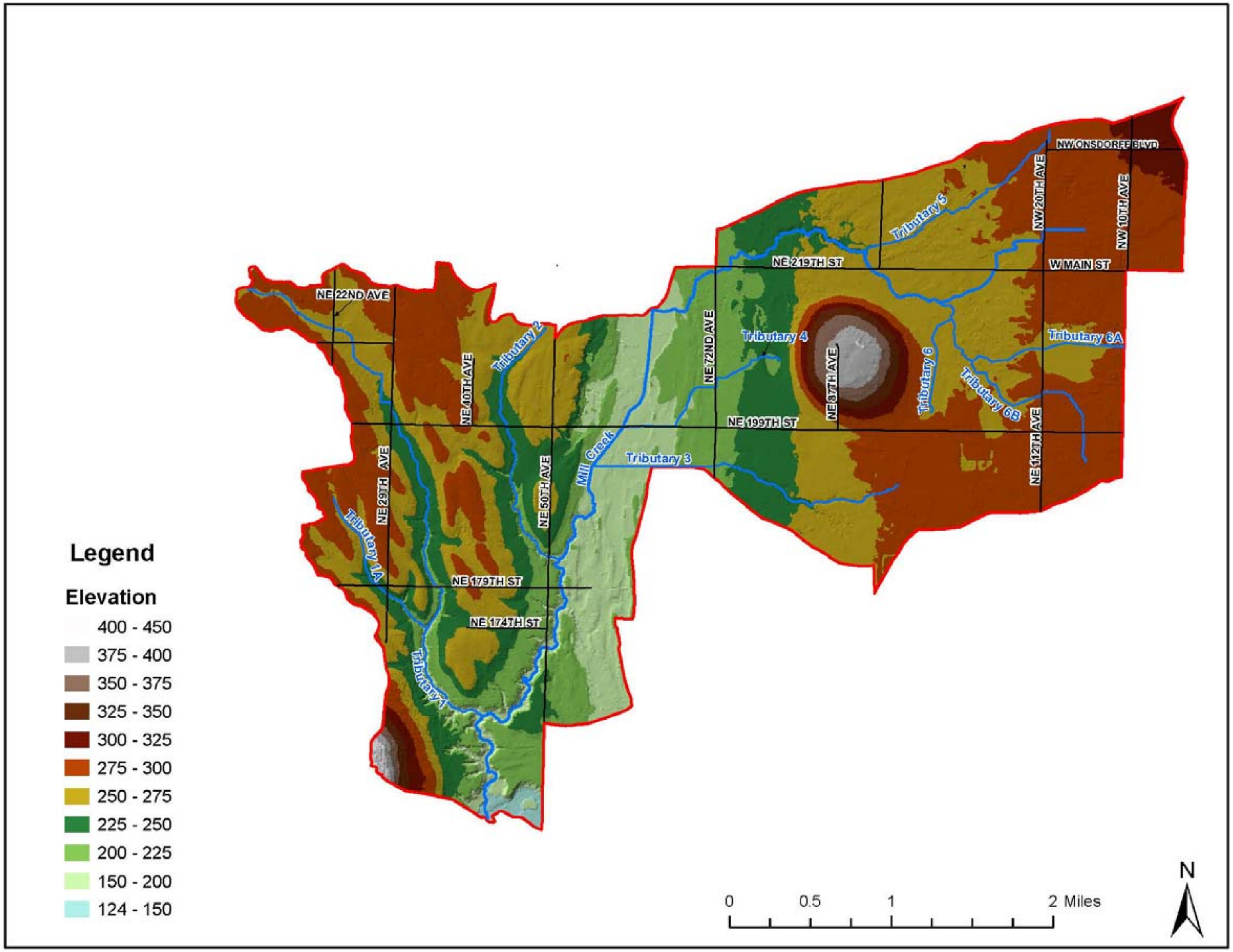


**Figure 5. Topographic relief map of the Mill Creek Basin.**

### 3.1.6 Land Cover and Land Use

#### 3.1.6.1 Historic

Historic land use conditions in the Mill Creek basin are not well documented. Cadastral survey maps (Figure 6) and surveyors notes from 1858 (BLM, 2008) show that a significant portion of the basin was forested with Fir, Maple, Ash, Oak and Alder with an undergrowth of Hazel, Willow and Vine Maple. A significant sized north-south trending marshy area was present in the central portion of the basin. Several smaller marshes were present in both the eastern and western portions of the basin. Several tributary stream channels were mapped in the western portion of the basin. In the eastern portion of the basin, a single channel was present and although not shown, likely terminated at the large north-south trending marshy area previously mentioned. It appears that the existing system of channels was expanded after 1858 in an attempt to improve drainage conditions to facilitate agriculture. No farms, roads or other types of land alterations appear to have been present within the basin in 1858. Available historic aerial photography indicates that much of the native forests had been cleared and the land converted for agricultural use by the year 1955. The current system of drainage channels was also substantially developed by 1955. However, recent urban developments have altered the locations of some of these channels.

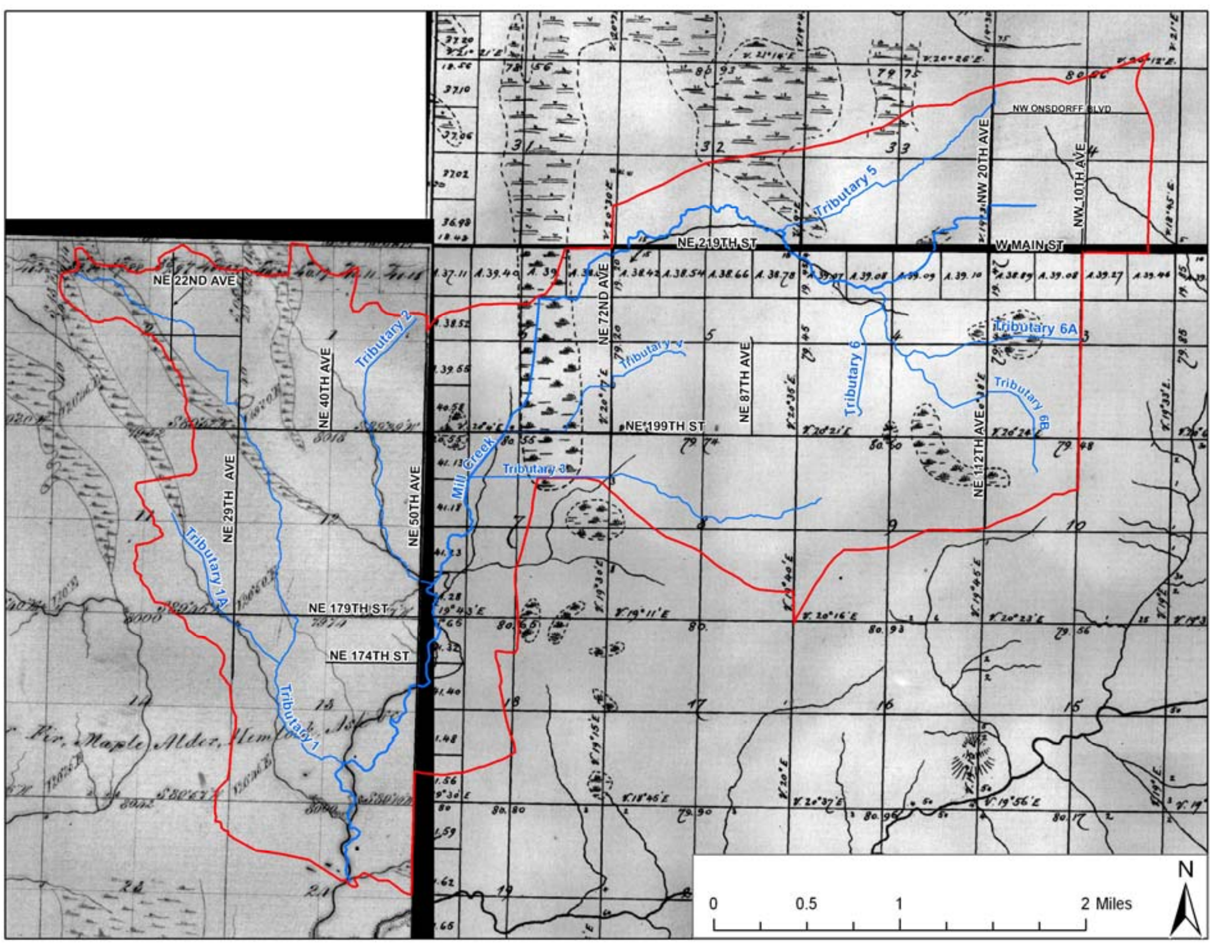


**Figure 6. 1858 cadastral survey maps (BLM, 2008) for Mill Creek overlain with drainage basin boundary and current channel location.**

#### 3.1.6.2 Current

The current basin land use consists primarily of suburban residences and commercial developments in the eastern portion of the basin around the City of Battleground and in the southwestern portion of basin near the Washington State University Vancouver Campus. The remaining areas within the basin are a mix of rural residential and agriculture. Patches of forest land are interspersed throughout the basin but are more prominent along narrow riparian corridors in the southern portion of the basin and in larger tracts in the northern portion of the basin. In 2007, the basin land cover was 15.8% forested, 36.6% residential, 8.1% impervious, and 36.4% non-canopy (Figure 7).

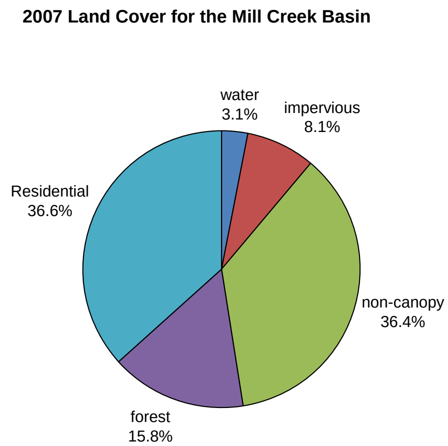


**Figure 7. Land cover characteristics for the Mill Creek basin (WEST, 2008)**

#### 3.1.6.3 Future

Future land use for the Mill Creek basin is characterized in the document "Clark County 20-Year Comprehensive Growth Management Plan 2004-2024". The current land use zoning for the basin was extracted from the accompanying GIS coverage and is provided in Table 2.

**Table 2. Land Use Zoning in Mill Creek Basin**

| Zone | Percentage of Curtin Creek Basin |
|---|---|
| Urban | 59.3 |
| Rural Residential | 27.3 |
| Agricultural | 12.2 |
| Parks and Open Space | 1.2 |

As seen in the table, approximately 12.2 percent of the basin is zoned for agricultural use, 27.3 percent is zoned for rural residential development, and 1.2 percent is zoned for parks and open space. These areas would be expected to have minimal increases in impervious surface area and therefore the least impact on future hydrologic conditions resulting from build out of the current comprehensive plan and zoning. The zoning for the remaining 59.3 percent of the basin is a mix of urban industrial, commercial and residential development which would be expected to have the highest proportion of impervious area and therefore the largest impact on future hydrologic conditions resulting from build out of the current comprehensive plan and zoning.

A land use zoning map is provided in Figure 8. As seen in the figure, the areas that are expected to have the greatest increase in impervious surface area and therefore the greatest impact on future hydrologic conditions are located in the lower portion of the basin south of 199$^{th}$ Street and in the eastern portion of basin east of NE 92$^{nd}$ Avenue. The central and northern portions of the basin are expected to have only minimal increases in impervious areas and therefore the least impact on future hydrologic conditions.

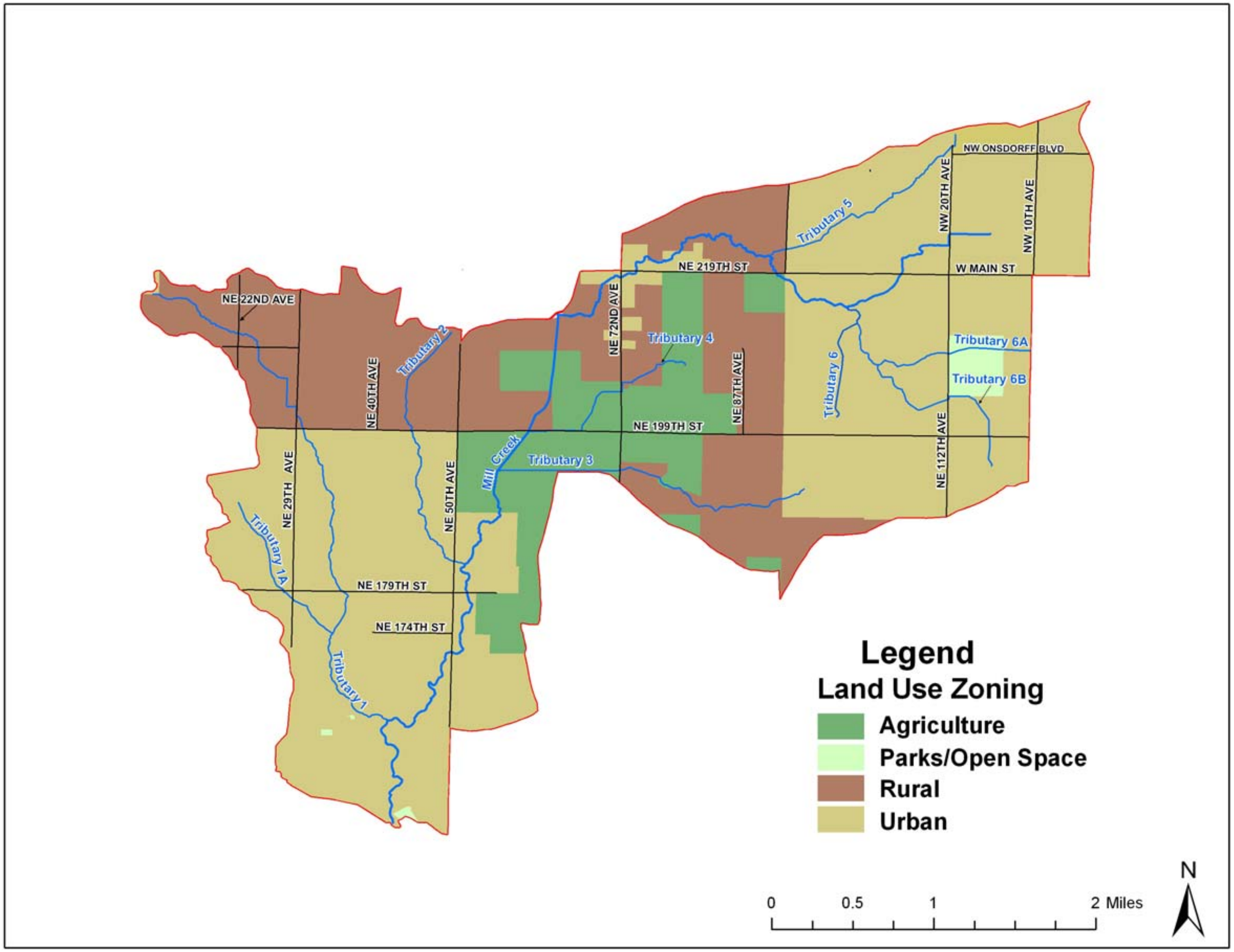


**Figure 8. Land use zoning (data from Clark County Comprehensive Growth Management Plan).**

### 3.1.7 Hydromodifications

Hydromodifications that have occurred in the Mill Creek basin include the following: flow diversions, private dams and associated ponds; stormwater detention ponds; stormwater piping, culvert and bridge stream crossings; and drainage ditches in fields and along roadways. Direct water withdrawal from streams for irrigation purposes may also be occurring, but identification of their location and extent was beyond the scope of this investigation.

#### 3.1.7.1 Flow Diversions

A drainage diversion ditch was constructed between Mill Creek and the Mill Creek tributary to the E.F. Lewis River. The diversion is located approximately 900 feet downstream of NE 67$^{th}$ Avenue. The connection results in a diversion of a portion of flow out of the Mill Creek basin. The percentage of flow diverted is unknown and is likely controlled by the local hydraulic conditions of each channel near the junction.

#### 3.1.7.2 Dams and Ponds

Private dams and associated ponds have been observed along both the main stem and tributary reaches of Mill Creek. However, these types of modification are not prevalent in the basin. The ponds appear to be either for aesthetic/recreational purposes, or for irrigation/livestock use. The associated ponds are likely trapping fine sediment; but are disrupting the transport of bed material. The ponds may also be responsible for incremental increases in water temperature during parts of the year resulting from increased exposure to solar radiation. Fecal coliform contamination from waterfowl is an additional concern.

#### 3.1.7.3 Stormwater Facilities

Stormwater detention basins are associated with more recent residential and commercial development in the Mill Creek basin. Stormwater detention ponds temporarily store excess runoff that results from the construction of impervious surfaces. The detention ponds are typically designed to control peak flows and are likely increasing the duration of moderate flows that over time may result in the incision and subsequent instability of downstream channels. Stormwater piping is found mostly in the southern and eastern portions of the basin where there are a greater number of high density residential neighborhoods and commercial developments compared to the northern and central portion of the basin which are more rural.

#### 3.1.7.4 Drainage Ditches

As previously mentioned, the system of stream channels was expanded to include a network of ditches that were originally constructed to improve drainage conditions for agriculture. When combined with the smaller drainage ditches that exist in farm fields and along roadways, the drainage density in the basin is greater than would otherwise occur. The increased drainage density results in a reduction in the time of concentration and therefore quicker runoff response to precipitation and increased peak flows. Drainage ditches also reduce the amount of water that would otherwise infiltrate into the surrounding soils and later be released to the streams as base flow during dry periods. In locations where treatment facilities have not been developed, roadway drainage ditches may convey pollutants that are washed from the road surface and conveyed directly to stream channels.

#### 3.1.7.5 Hydraulic Structures

Culvert and bridge crossings locally modify the hydraulics of the stream both upstream and downstream of the structure. This effect usually results in a disruption in the natural sediment transport characteristics of the involved stream channel. In locations where the size of the hydraulic opening is restricted, backwater conditions will occur during moderate and high flows. Reduced stream velocities and shear stresses due to backwater often result in increased sediment deposition upstream of the hydraulic structure and decreased sediment supply to downstream reaches.

If significant floodplain storage is available upstream of the structure, temporary storage of flood waters can occur and result in a reduction in downstream peak flows. In contrast to upstream hydraulic conditions, downstream of the structure, stream velocities and shear stresses are locally increased by the restricted hydraulic opening. If not mitigated by an energy dissipation device, this usually results in scour of the channel bed material that often leaves the culvert outlet invert perched above the downstream water surface during moderate and low flows. If the disruption in sediment transport by the hydraulic structure is significant, degradation of downstream reaches may occur. Similarly, culverts and bridges affect the ability of the stream channels to migrate. This impact may alter sediment transport and the form of the upstream and downstream channel.

Figure 9 shows a channel shear stress profile of Mill Creek developed from the updated HEC-RAS hydraulic model (WEST, 2008). The RAS model includes future conditions flows for Mill Creek based on the updated HSPF hydrologic model (WEST, 2008). For the evaluation, the threshold for channel instability, which is assumed to be one-half of the 2-year event based on work by Booth (1989) which for Mill Creek is equivalent to the 1.1-year flood event (WEST, 2008), was used. As seen in the figure, the channel shear stress for the 1.1-year recurrence interval flood is significantly reduced upstream of and significantly increased downstream of various road crossings, most notably a private bridge near RM 1.2 as well as multiple public and private road crossing between RM 4.5 and 5.2. Local scour, channel incision, and bank failures were observed in this reach.

Channel shear stress is also seen to increase downstream of NE 159th Street to the confluence with Salmon Creek. Along this reach, Mill Creek is seen to have a steeper gradient than the reach immediately upstream. As seen in Figure 9, the future conditions 1.1-year flow is not expected to significantly alter the magnitude of channel shear stress. At RM 3.2 and RM 5.2, channel shear stress is significantly reduced for future conditions flows. Although the magnitude of the 1.1-year flow for future conditions is greater than for existing conditions, the higher discharge results in greater backwater from the culverts located downstream of these two locations. The increased backwater elevation reduces channel velocities and shear stresses.

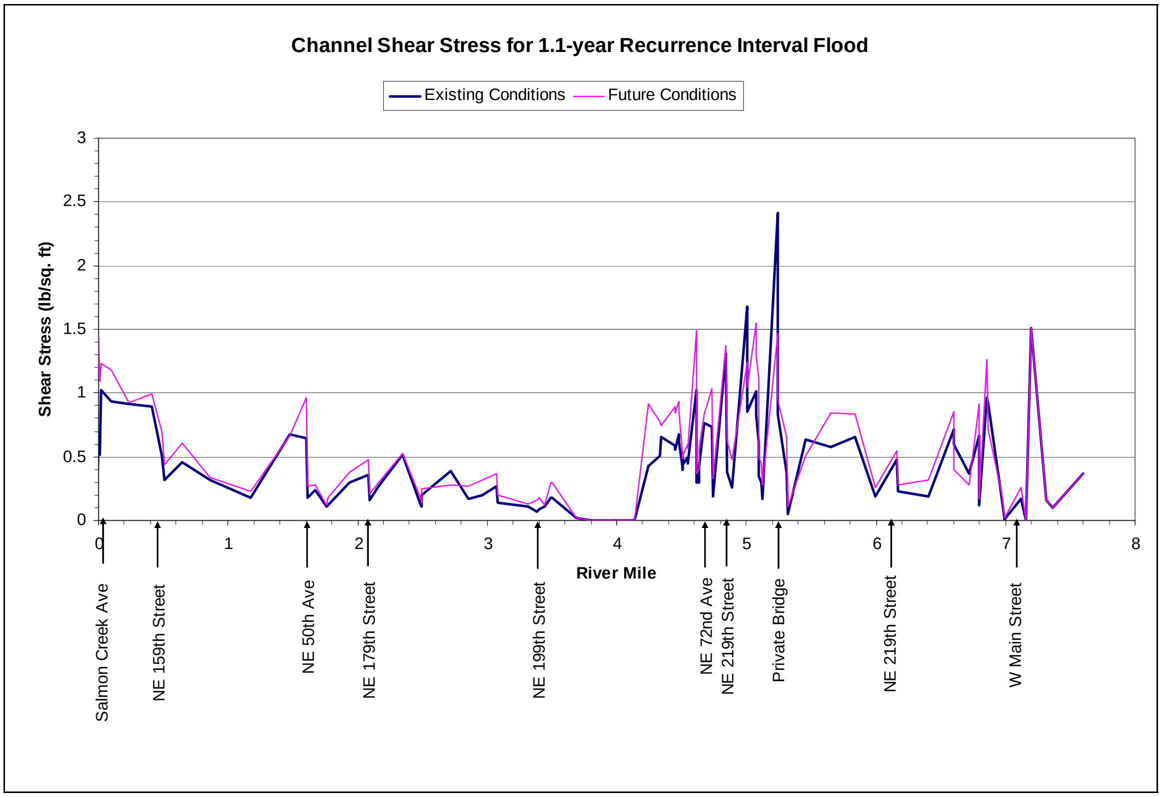


**Figure 9. Channel shear stress profile for 1.1-year flood along Mill Creek (WEST, 2008).**

As seen in Figure 10, the relative percentage of the total 10-year peak flood discharge conveyed in the floodplain is influenced by several existing road crossings. Backwater conditions upstream from the road culverts and bridges result in a greater portion of the total discharge being conveyed within the floodplain. Downstream of the culverts and bridges, the discharge is often confined to the channel. It should also be noted that the stream reaches with the greatest percentage of flow in the floodplain shown in Figure 10 are seen in Figure 9 to have the lowest values of shear stress while the more confined reaches which have little or no flow in the floodplain have larger values of shear stress.

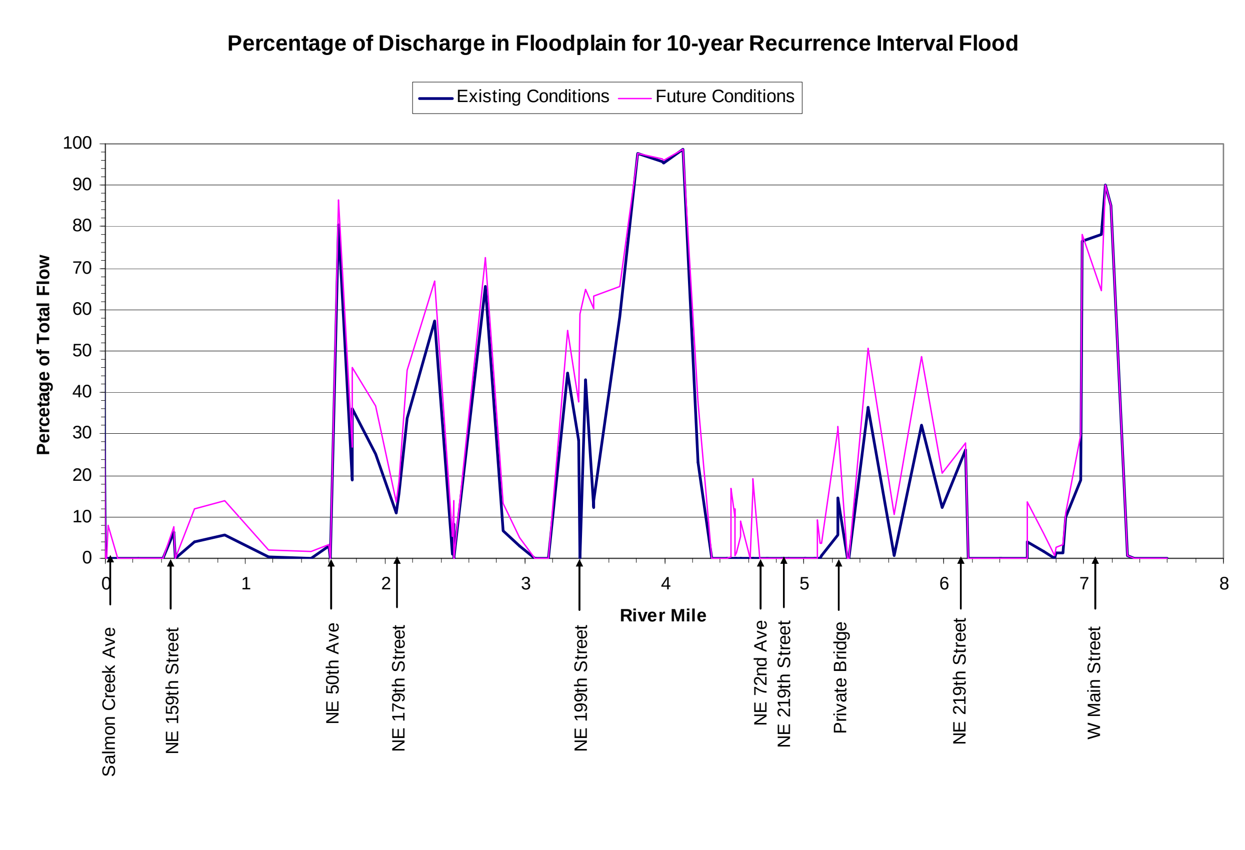


**Figure 10. Percentage of total existing and future conditions 10-year peak discharge conveyed in the Mill Creek floodplain (WEST, 2008)**

### 3.1.8 Conclusions

- As discussed in Section 3.2, the upper and lower portions of the Mill Creek basin are expected to experience additional impacts to future hydrologic conditions resulting from build out of the current comprehensive plan and zoning. These areas are likely to experience changes to the geomorphic characteristics of the stream channels. Although future land use conditions in the middle portion of the basin are not expected to change significantly from current conditions, this area is likely to undergo morphologic change as peak flows and/or flow durations originating in the upper portion of the basin increase. It should be noted that the future conditions hydrologic model described in Section 3.2 does not consider stormwater control facilities that would be implemented by current development code or the so to be effective revisions to the code under the county's 2007 NPDES permit. Therefore, future conditions flow increases may not be as severe as predicted. Consequently, the magnitude of potential future morphologic changes may be reduced.

- Although not prevalent in the basin, dams and associated ponds have resulted in localized alterations to the natural hydrologic, geomorphic and water quality conditions of Mill Creek. This is resulting in alterations to the sediment transport conditions, elevation of water temperatures, and is contributing to increased contamination from waterfowl.

- Stormwater detention facilities will need to be designed to manage peak flows and flow durations of erosive discharges. Otherwise, channel incision, headcutting and subsequent bank failures will continue to occur. Degradation of the channel will be especially pronounced in the steeper gradient stream reaches and downstream of hydraulic structures that currently exhibit relatively high values of shear stress.

- Drainage ditches have increased drainage density resulting in the drainage of natural wetlands, increased peak flows, and reductions in groundwater recharge. Where treatment facilities are not installed, drainage ditches convey pollutants directly to stream channels.

- Culverts and bridges are altering sediment transport conditions and locally prevent channel migration. Culvert/bridge crossings at Salmon Creek Ave, NE 50th Ave, NE 179th Street, NE 199th Street and multiple private culverts were seen to have channel degradation and/or local scour occurring downstream. Unless mitigated, future increases in peak flows and/or flow durations will exacerbate existing scour conditions at these locations.

- Culvert and bridge crossings significantly influence the amount of floodwaters that are conveyed and/or stored in the floodplain. Replacement of culverts or bridge with structures having greater hydraulic efficiency and therefore less backwater, will result in greater concentration of flows in the channel and less floodplain connectivity immediately upstream of the structure. The replacement may also result in increased flows downstream of the structure as a result of lost floodplain storage. Unless mitigated, localized impacts to the stream channel in the form of incision and bank failures will occur. Mitigation could be in the form of woody debris jams and grade control structures. The installation of woody debris jams will result in increased channel roughness, reduced stream velocities and shear stresses, higher water surface elevations, and greater connectivity between the channel and floodplain. Grade control structures would help prevent channel incision.

### 3.1.9 Recommendations

- Develop projects that restore the hydrologic and habitat functions of areas that historically were considered wetlands. Specifically, wetland restoration projects located within the wide valley bottom containing Mill Creek located between NE 67th Ave and the confluence of Tributary 3 which is located just south of NE 199th Street. Figure 6 indicates that there may be additional opportunities for wetland restoration projects within the subbasin of Tributary 6. These projects would help protect the middle and lower reaches of Mill Creek by helping reduce future increases in erosive flows.

- It is noted that the land use zoning map provides a broad level of detail regarding land use for a 20-year period (2004-2024). Those portions of the basin that are expected to experience the least amount of development over this time period should not be ignored. Reestablishment of riparian corridors along the middle portion of Mill Creek will provide greater protection to the stream channel as development pressure in the upper portion of the basin increases in the future.

- Dams and associated ponds should be individually evaluated to determine the impact each is having on the hydrology, water quality and geomorphology of the involved stream. This could be used to prioritize both modifications to and/or removal of existing structures.

- Infiltration facilities should be considered the preferred option for disposal of stormwater in areas where site specific soil and groundwater conditions are appropriate.

- Existing and future stormwater detention facilities should be evaluated through the use of continuous simulation hydrologic modeling to understand the magnitude of modifications to the duration of flows compared to predevelopment conditions.

- Ensure appropriate BMPs are being implemented with regard to maintenance of drainage ditches and discourage the development of new drainage ditches that have a direct connection to natural channels.

- Use geomorphically based performance standards when designing and constructing new or replacement hydraulic structures at road crossings. Designs should allow for lateral and longitudinal continuity and connectivity of both the channel and functional floodplain in addition to hydraulic design considerations. Potential upstream and downstream impacts resulting from the replacement structure and mitigation for these impacts must be considered during design. Mitigation in the form of woody debris jams and grade control or other appropriate measures should be installed to offset the loss of floodplain connectivity and channel incision that would likely occur as a result of the replacement structure.

- Replace culverts or install energy dissipation devises downstream of culverts where scour has degraded the downstream channel. Culvert crossings at NE $50^{th}$ Ave, NE $179^{th}$ Street, NE $199^{th}$ Street and multiple private culverts are exhibiting these conditions.

## 3.2 Hydrology

### 3.2.1 Drainage Basin

The Mill Creek basin is approximately 11.9 square miles in total area. A summary of tributary drainage basin areas is provided in Table 3. Average annual precipitation over the basin is 48 inches (NRCS, 1998). Mill Creek is a $3^{rd}$ order tributary to Salmon Creek and is approximately 8 miles in length. Ninety-five percent of the stream channels in the Mill Creek basin are considered head water streams ($1^{st}$ or $2^{nd}$ order) (Wierenga, 2005). Approximately 3.6 percent of the basin is mapped as wetland and 2.8 percent is mapped as floodplain (Wierenga, 2005). The percentages of wetland and floodplain area suggest that portions of the basin will store and attenuate flood waters.

**Table 3. Mill Creek drainage basin areas.**

| Stream | Drainage Area (sq. mi.) | Percent of Total |
|---|---|---|
| Mill Creek | 11.9 | 100 |
| Tributary 1 | 2.12 | 17.9 |
| Tributary 2 | 1.14 | 9.6 |
| Tributary 3 | 1.12 | 9.4 |
| Tributary 4 | 0.75 | 6.3 |
| Tributary 5 | 0.59 | 5.0 |
| Tributary 6 | 1.62 | 13.7 |

Approximately, 13 percent of the basin soils are type B (well drained), while the remaining 87 percent of the basin soils are type C/D (moderate to poorly drained). This indicates that there is a greater tendency for precipitation over the basin to contribute to surface runoff rather than infiltrate for high intensity and/or longer duration storm events that exceed soil infiltration rates. For short duration and/or low intensity storm events, a greater portion of the precipitation is likely infiltrated. Runoff rates increase in the mid and late winter months after the soil moisture levels in the basin have been replenished by late fall and early winter storm events.

### 3.2.2 Stream Flow Conditions

A stream gage located at the WSU campus near the mouth of Mill Creek has been in operation since May 2003. The gage has a drainage area of 11.6 square miles, which is approximately 0.3 square miles smaller than the Mill Creek Basin (11.9 square miles).

Mean monthly discharges for water years 2003 through 2007 are shown in Figure 11. As seen in the figure, the highest flows occur during the winter and spring months with lows flows occurring during the summer and early fall months. Mean annual flow for Mill Creek at the gage is 14 cfs. The estimated mean annual discharge based on output from the HSPF hydrologic model (WEST, 2008) is 19.7 cfs.

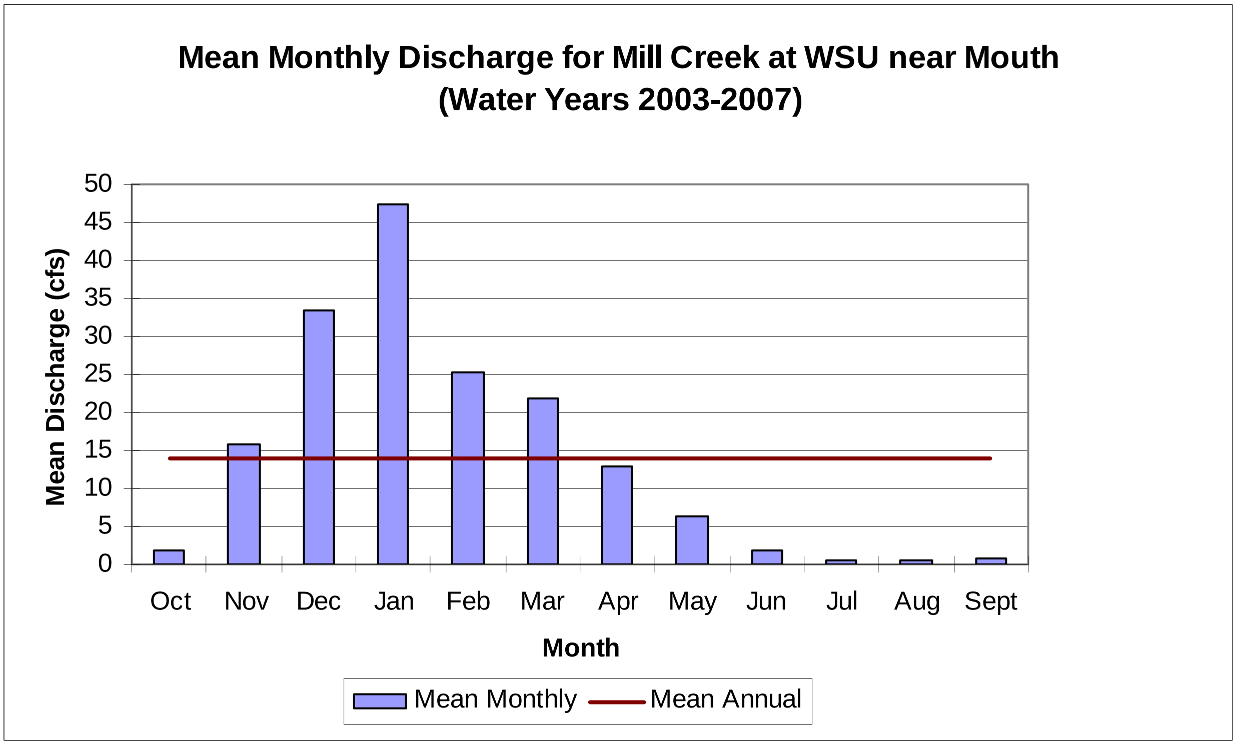


**Figure 11. Mean Monthly Discharge for Mill Creek at WSU near Mouth.**

The lower magnitude flows that occur during the summer and early fall months are a result of multiple contributing factors. The largest contributing factor is the temperate marine climate which tends to favor wet winters and dry summers. Additionally, the majority of the basin soils have relatively low infiltration capacities, causing much of the wintertime precipitation to run off rather than be stored in the soils and bedrock for later release to the streams. Also, the well drained topography, high channel density and general lack of functional wetlands limits groundwater recharge. This may be exacerbated by surface water withdrawals for irrigation during the summer growing season. Lastly, continued increases in the amount of impervious surfaces has further reduced infiltration and increased wintertime runoff volumes. As of 2007, the total impervious area represented approximately 8.1 percent of the basin.

The maximum mean daily discharge for water years 2003 through 2007 was 180 cfs, which occurred on December 15, 2006. Figure 12 shows a flood hydrograph for December 11 to December 21, 2006 at the WSU gage. Within a 16 hour time period the stream discharge increased from 46 cfs to 260 cfs, indicating that the basin has a relatively flashy response to precipitation.

A quantitative indicator of the flashiness of a basin is the value of $T_{Qmean}$, which is the portion of time mean daily flows exceed the mean annual flow. Low values of $T_{Qmean}$ are often associated with urbanized watersheds. The redistribution of water from base flow to surface runoff will decrease the fraction of time that daily discharges exceed the mean discharge. Therefore, the higher the $T_{Qmean}$ value, the more stable or less flashy the stream. An investigation of urban and rural streams in the Puget Sound (Booth, et al, 2001) found that urban streams tended to have $T_{Qmean}$ values of less than 0.3 while suburban streams have values greater than 0.3. $T_{Qmean}$ for Mill Creek calculated from the available data for the WSU gage is 0.28. Daily flows for Mill Creek generated from the HSPF model for existing and proposed conditions were also used to determine $T_{Qmean}$. Existing and future conditions values of $T_{Qmean}$ are 0.33 and 0.31, respectively. Values of $T_{Qmean}$ for Mill Creek generated from the gage data are relatively low and are typical for an urbanized watershed while the values generated from the HSPF model are somewhat high and are more representative of suburban watersheds. The discrepancy between the gage data and the existing conditions HSPF model is likely the result of the relatively short period of record for the gage compared to the much longer period of record used to develop the HSPF model results. Therefore, the values of $T_{Qmean}$ developed from the HSPF model are likely more representative of the Mill Creek basin. The value of $T_{Qmean}$ generated from the future conditions HSPF model suggest that, if not mitigated, Mill Creek will become flashier in the future resulting in increased peak flows and reduced summer low flows. It is noted that the majority of existing urban development in the Mill Creek basin is located in the upper basin in and around the City of Battleground. Values of $T_{Qmean}$ generated from the existing and future conditions HSPF model for this area are 0.31 and 0.28, respectively. This suggests that impacts to flows resulting from urbanization are more significant in the upper basin than in the lower basin.

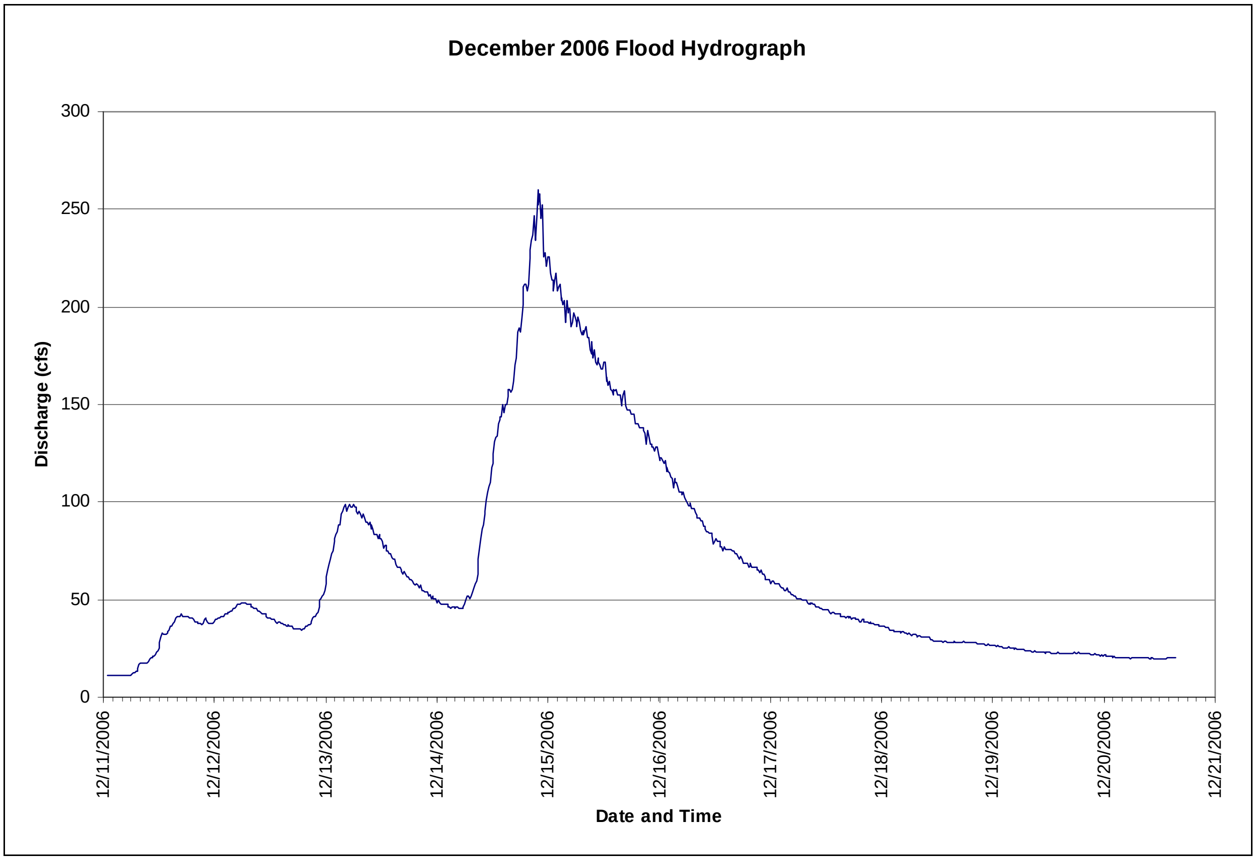


**Figure 12. December 2006 flood hydrograph for Mill Creek at WSU.**

### 3.2.2.1 Peak Discharges

The period of record for the Mill Creek gage at WSU is not sufficient to conduct a flood frequency analysis. Therefore, peak discharges and associated recurrence intervals for Mill Creek were estimated using a HSPF hydrologic model for the Mill Creek basin (WEST, 2008) which included several Mill Creek subbasins. Existing and future conditions peak flows for selected locations along Mill Creek are shown in Table 4.

Available stream flow records indicate that annual peak discharges for water years 2003 to 2007 ranged from 80 to 260 cfs. In the last five years, peak discharges have been below the magnitude of a 2-year recurrence interval flood. The peak flow on December 3, 2007 was 413 cfs which has a recurrence interval of approximately 5-years.

**Table 4. Estimated peak discharges for Mill Creek**

| Location | Drainage Area ($mi^2$) | Recurrence Interval (yrs) | Existing Discharge (cfs) | Future Discharge (cfs) |
|---|---|---|---|---|
| Mill Creek basin at streamflow gage near outlet | 11.64 | 2 | 277 | 454 |
| | | 10 | 512 | 787 |
| | | 20 | 611 | 931 |
| | | 50 | 747 | 1,134 |
| | | 100 | 857 | 1,300 |
| | | 500 | 1,137 | 1,736 |
| Mill Creek at NE 179th Street | 8.52 | 2 | 202 | 275 |
| | | 10 | 357 | 451 |
| | | 20 | 429 | 527 |
| | | 50 | 534 | 637 |
| | | 100 | 623 | 727 |
| | | 500 | 871 | 971 |
| Mill Creek at NE 199th Street | 6.84 | 2 | 169 | 237 |
| | | 10 | 284 | 383 |
| | | 20 | 330 | 450 |
| | | 50 | 391 | 548 |
| | | 100 | 439 | 631 |
| | | 500 | 558 | 863 |
| Mill Creek at intersection of NE 72nd Avenue and NE 219th Street | 4.37 | 2 | 177 | 314 |
| | | 10 | 338 | 504 |
| | | 20 | 411 | 582 |
| | | 50 | 518 | 689 |
| | | 100 | 608 | 774 |
| | | 500 | 853 | 992 |
| Mill Creek near intersection of NE 219th Street and NE 92nd Avenue | 3.64 | 2 | 165 | 306 |
| | | 10 | 325 | 506 |
| | | 20 | 402 | 590 |
| | | 50 | 518 | 707 |
| | | 100 | 617 | 800 |
| | | 500 | 901 | 1,042 |

#### 3.2.2.2 Flow-Duration

Existing and future conditions flow-duration curves for Mill Creek are provided in Figure 13. As seen in the figure, the existing and future conditions flow-duration curves diverge from one another at approximately 20 cfs. For future conditions, the duration of flows greater than 20 cfs is expected to increase while flows less than 20 cfs are expected to have roughly the same duration. Flows are expected to equal or exceed 20 cfs approximately 35 percent of the time. Therefore, approximately 65 percent of the time, future flow conditions will be about the same as for existing conditions.

As seen in Figure 13, the flow-duration curve developed for the gage (located near WSU) is much lower than both the existing and proposed conditions curves developed from the HSPF model. As was previously noted, the period of record for the gage is rather short compared to the existing and future conditions HSPF model (WEST, 2008) Therefore, the gage data may not fully represent the flow-duration conditions of the basin.

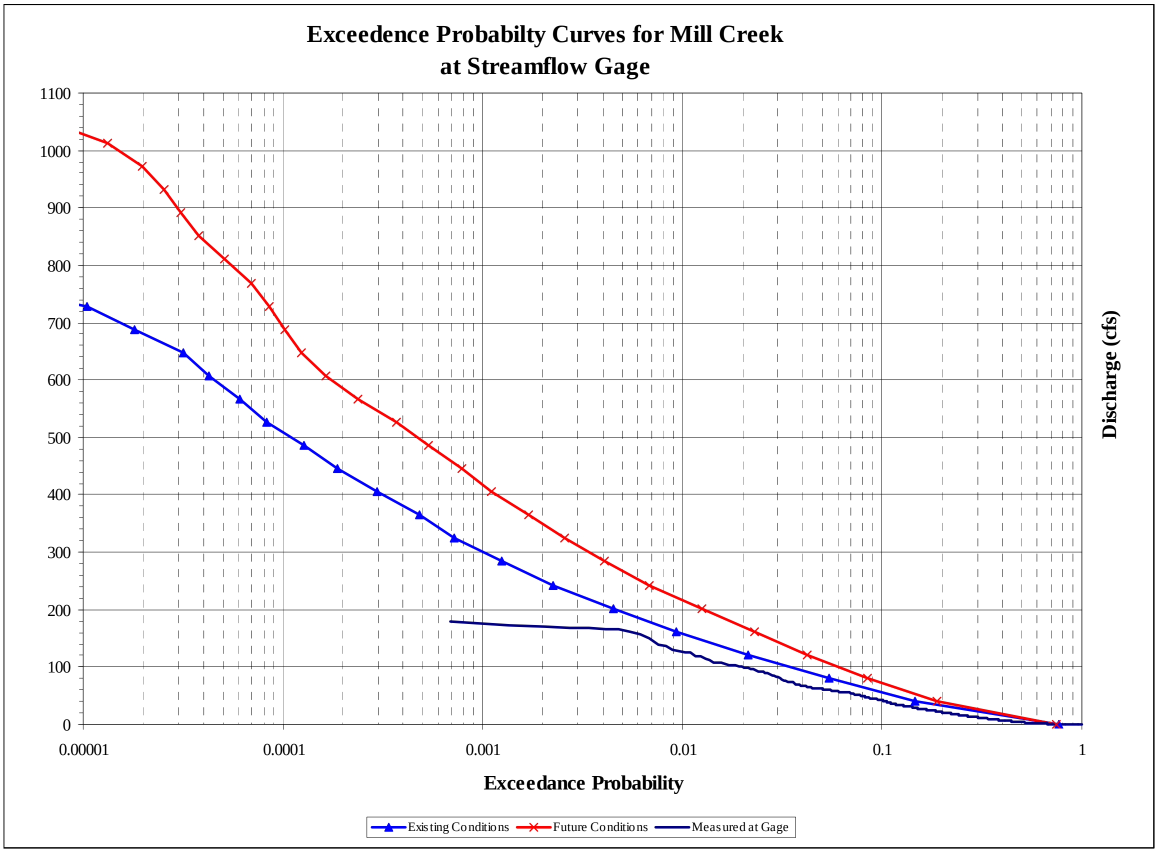


**Figure 13. Flow-duration curves for Mill Creek at WSU gage.**

### 3.2.2.3 Low Flow Conditions

The available period of record for the Mill Creek gage at the WSU campus is not sufficient for developing low flow statistics. However, low flow statistics developed from the HSPF hydrologic model for Mill Creek (MGS, 2002) are provided in Table 5. As seen in the table, future low flows are not expected decrease slightly compared to existing conditions. The minimum mean daily flow recorded at the gage was 0.14 cfs which occurred late August and early September, 2003 and again in early September 2005. During efforts to collect sediment samples on August 14, 2008, Mill Creek was observed to be completely dry in several locations with stagnant or near zero velocity flow at remaining sample sites.

**Table 5. 7-day low flow magnitude-frequency statistics for Mill Creek**

| | Discharge (cfs) | | | | |
|---|---|---|---|---|---|
| Recurrence Interval | 1.25-yr | 2-yr | 5-yr | 10-yr | 25-yr |
| Existing Conditions (cfs) | 2.1 | 1.9 | 1.6 | 1.2 | 1.1 |
| Future Conditions (cfs) | 2.0 | 1.8 | 1.5 | 1.1 | 1.0 |

### 3.2.3 Conclusions

- The wetland and floodplain areas that historically existed in the basin suggest that portions of the basin could be restored to enhance storage and attenuation of flood waters. Therefore, opportunities are likely to exist within the basin for enhancement of existing wetlands and floodplains for the purpose of increasing available flood storage.

- The $T_{Qmean}$, a measurement of "flashiness", for Mill Creek at the WSU gage is 0.33 and 0.31 for existing and future conditions, respectively. $T_{Qmean}$ for Mill Creek in the upper basin is 0.31 and 0.28 for existing and future conditions, respectively. The existing conditions values are more typical of suburban streams with minimal development. However, the future conditions values of $T_{Qmean}$ indicate that Mill Creek will become flashier in the future. This will be more pronounced in the upper basin near the City of Battleground which is zoned for urban development.

- A discussed in Section 3.3.2, bed and bank erosion problems were observed to be occurring in all reaches of Mill Creek except Reaches 3 and 7 (Reach locations are described is Section 3.3). Future changes in basin conditions that increase the duration of erosive flows, reduce riparian vegetation along channel banks, adversely alter hydraulic conditions, or impact sediment supply and transport will accelerate the existing degradation and increase the susceptibility of these reaches to further channel and bank erosion.

- The future conditions HSPF model does not consider stormwater control facilities that would be implemented by current development code or the so to be effective revisions to the code under the county's 2007 NPDES permit. Therefore, future conditions flows developed from the HSPF model are likely overestimated.

### 3.2.4 Recommendations

- Encourage the use of Low Impact Development (LID) measures for newly developing areas in the basin. LID focuses on minimizing the amount of runoff generated from the site by minimizing to the extent practical the amount of increased impervious surface area and infiltrating and treating stormwater runoff near the source in order to best mimic the predevelopment hydrologic conditions. Where soil conditions are a limiting factor on infiltration, LID practices should be combined with traditional stormwater detention/retention facilities.

- Continue monitoring stream flows at the WSU gage and consider the installation of an additional stream gage in the upper portion of the Mill Creek Basin near Dollar Corner (intersection of NE 219$^{th}$ Street and NE 72$^{nd}$ Avenue). $T_{Qmean}$ and other streamflows statistics can be used to help evaluate the effectiveness of stormwater management practices as future development occurs in the basin. However, flow monitoring at the WSU gage may not capture the extent of hydrologic changes that are occurring in the upper basin. An additional stream flow gage would allow for results that represent the upper portion of the Mill Creek basin and thus exclude the storage and attenuation of flows that occurs between approximately RM 2.8 and RM 4.2 (Reach 3 as described is Section 3.3).

- Conduct periodic updates to the recently developed continuous simulation hydrologic model of the Mill Creek basin to account for land use changes and any constructed regional stormwater facilities. This will provide an appropriate base condition to help evaluate changes in basin hydrology associated with proposed future development. The updated model would also help determine the magnitude and location of expected hydrologic changes and be useful to evaluate the effectiveness of potential stormwater facilities and/or mitigation projects.

- Develop more stringent stormwater flow control regulations that control peak discharges and the duration of erosive flows in order to help protect and restore stream channel and riparian habitat in the Mill Creek basin.

- Where appropriate, develop regional stormwater detention facilities and/or enhance existing wetland and floodplain storage areas to reduce hydrologic impacts to basin stream channels.

## 3.3 Geomorphology

### 3.3.1 Channel Profiles

The channel slope, sinuosity, and bed material size were used to divide the channel into 7 separate reaches of similar geomorphic characteristics which are summarized in Table 6. Reach locations are shown in Figure 14. As seen in the table, Reach 3 has the lowest sinuosity (1.0) and a very flat slope (0.0009). This reflects the anthropogenic origins of this channelized reach which was likely created to improve drainage conditions for agriculture. In contrast, the naturally formed channels comprising Reaches 1, 3, 4, 5, and 6 have greater sinuosity and steeper slopes. Reach 7 is contains both natural and modified subreaches but the characteristics of each are not different enough to justify further subdivision. A stream channel profile for Mill Creek (Figure 15) was developed from the updated HEC-RAS model (WEST, 2008) originally developed for the preliminary FEMA Flood Insurance Study (FEMA, 2006). The profile shows the reach limits and average channel slope for each defined reach.

**Table 6. Summary of reach characteristics**

| Reach | Extents | Average Slope | Sinuosity[1] | | Bed Material |
|---|---|---|---|---|---|
| 1 | Mouth to NE 159th Street | 0.011 | 1.23 | moderate | gravel/cobble |
| 2 | NE 159th Street to RM 2.8 | 0.002 | 1.14 | low | gravel/cobble/ sand |
| 3 | RM 2.8 to RM 4.2 | 0.0009 | 1.00 | low | sand |
| 4 | RM 4.2 to NE 219th Street (RM 6.2) | 0.005 | 1.09 | low | gravel/cobble |
| 5 | NE 219th Street to Private Bridge at RM 6.6 | 0.002 | 1.04 | low | sand/vegetation |
| 6 | Private Bridge at RM 6.6 to Private Bridge at RM 6.9 | 0.007 | 1.07 | low | sand/vegetation |
| 7 | Private Bridge at RM 6.9 to RM 7.6 | 0.004 | 1.03 | low | sand/vegetation |

1. Sinuosity is the ratio of the channel length to the valley length. The classification of sinuosity is based on Rosgen's Stream Classification System (1996)

Additionally, available topographic data were used to develop a DTM of the basin and extract ground profiles along the mainstem and tributary stream channel centerlines. The extracted ground profiles are shown in Figure 16, Figure 17, Figure 18, Figure 19, and Figure 20. Average slopes for each of the tributaries are summarized in Table 7. As seen in the table, Tributary 1A has the steepest slope. Although not depicted in the surface geology map shown in Figure 1, it is likely that the slope of Tributary 1A is controlled by the underlying coarse-grained Troutdale Formation. The remaining tributaries have slopes similar to Mill Creek.

**Table 7. Average Slopes for Tributaries to Mill Creek.**

| Tributary Name | Average Slope |
|---|---|
| 1 | 0.006 |
| 1A | 0.015 |
| 2 | 0.007 |
| 3 | 0.008 |
| 4 | 0.005 |
| 5 | 0.005 |
| 6 | 0.004 |
| 6A | 0.003 |
| 6B | 0.003 |

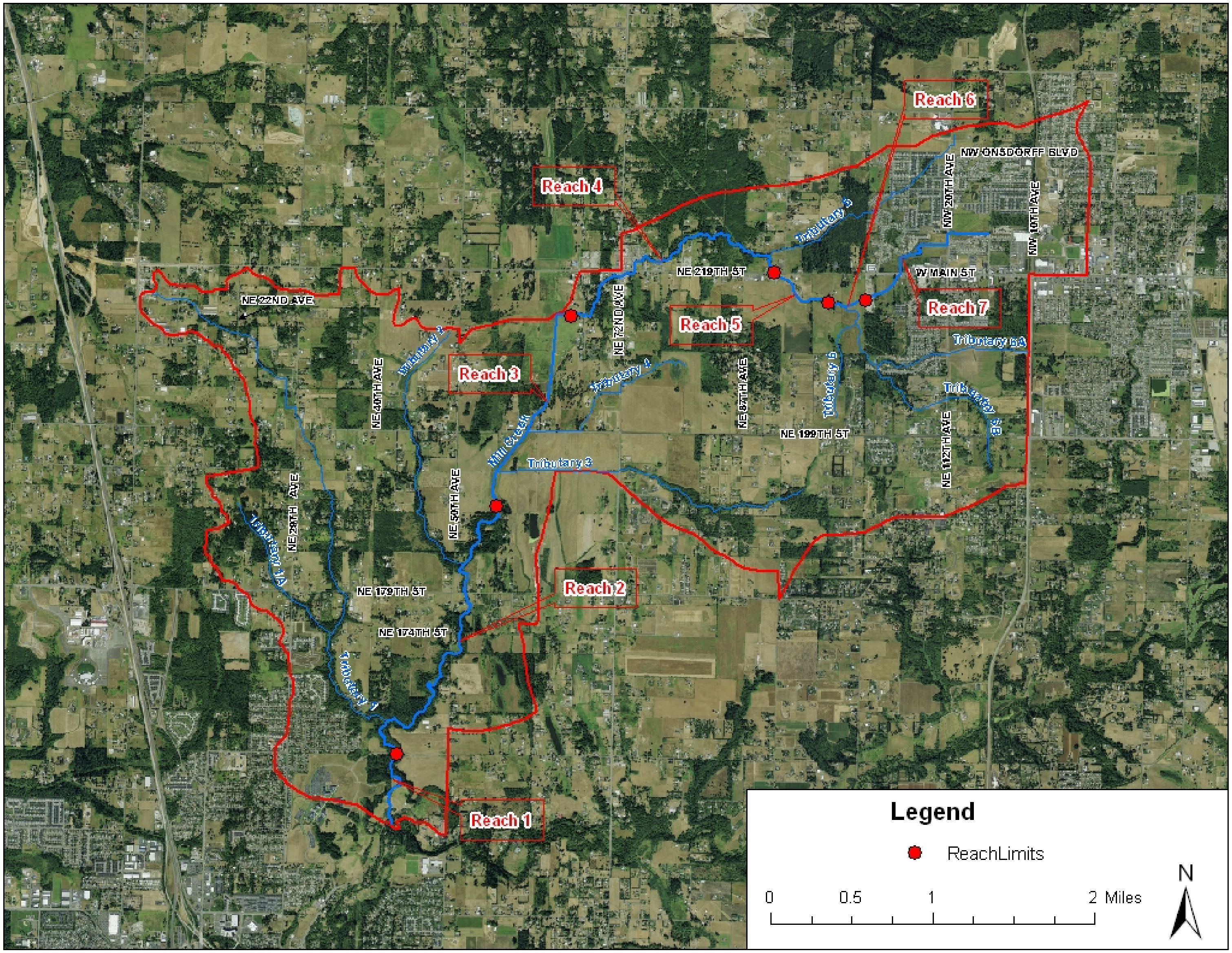


**Figure 14. Location of geomorphic reaches defined for Mill Creek.**

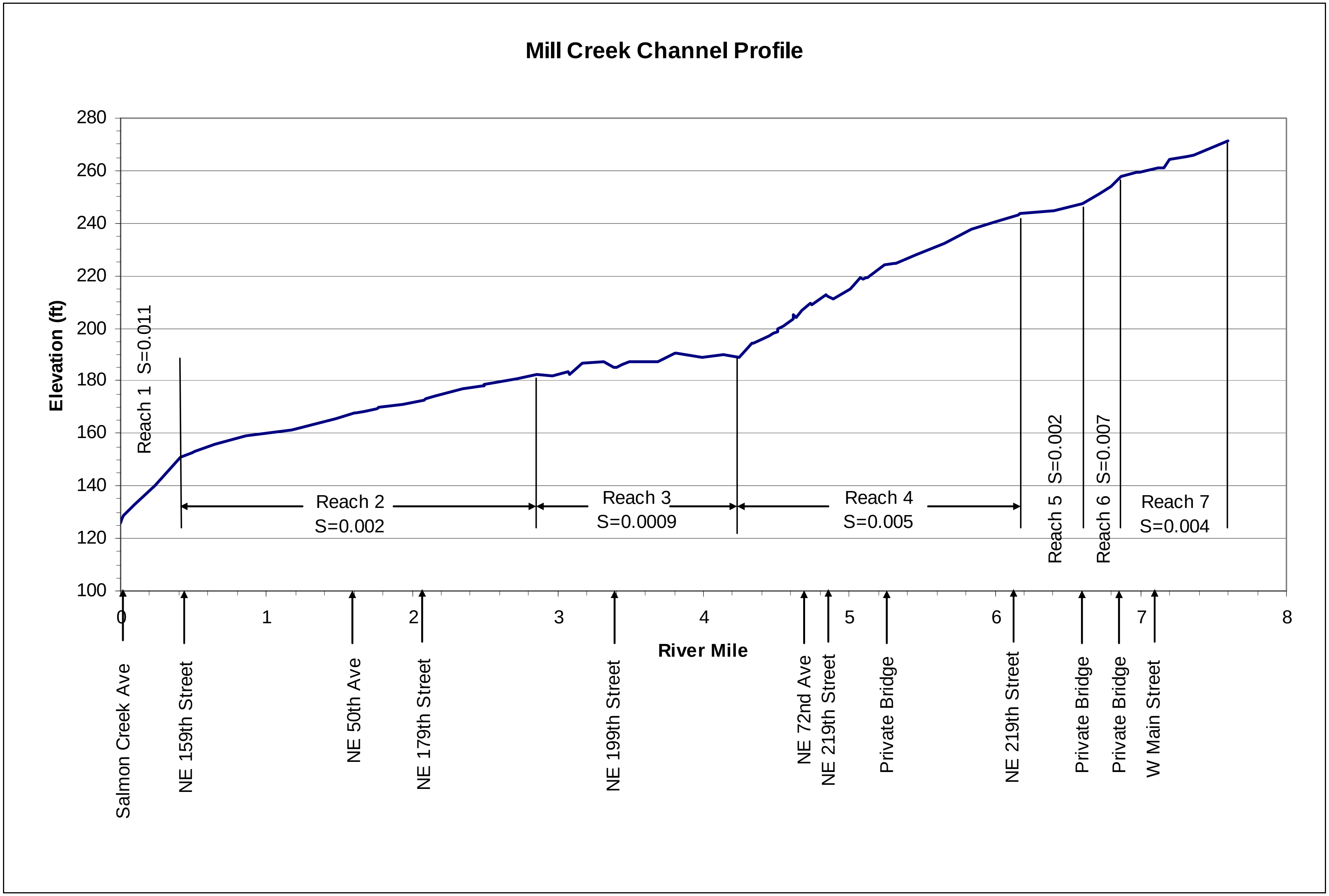


**Figure 15. Stream channel profile of Mill Creek (data from WEST, 2008).**

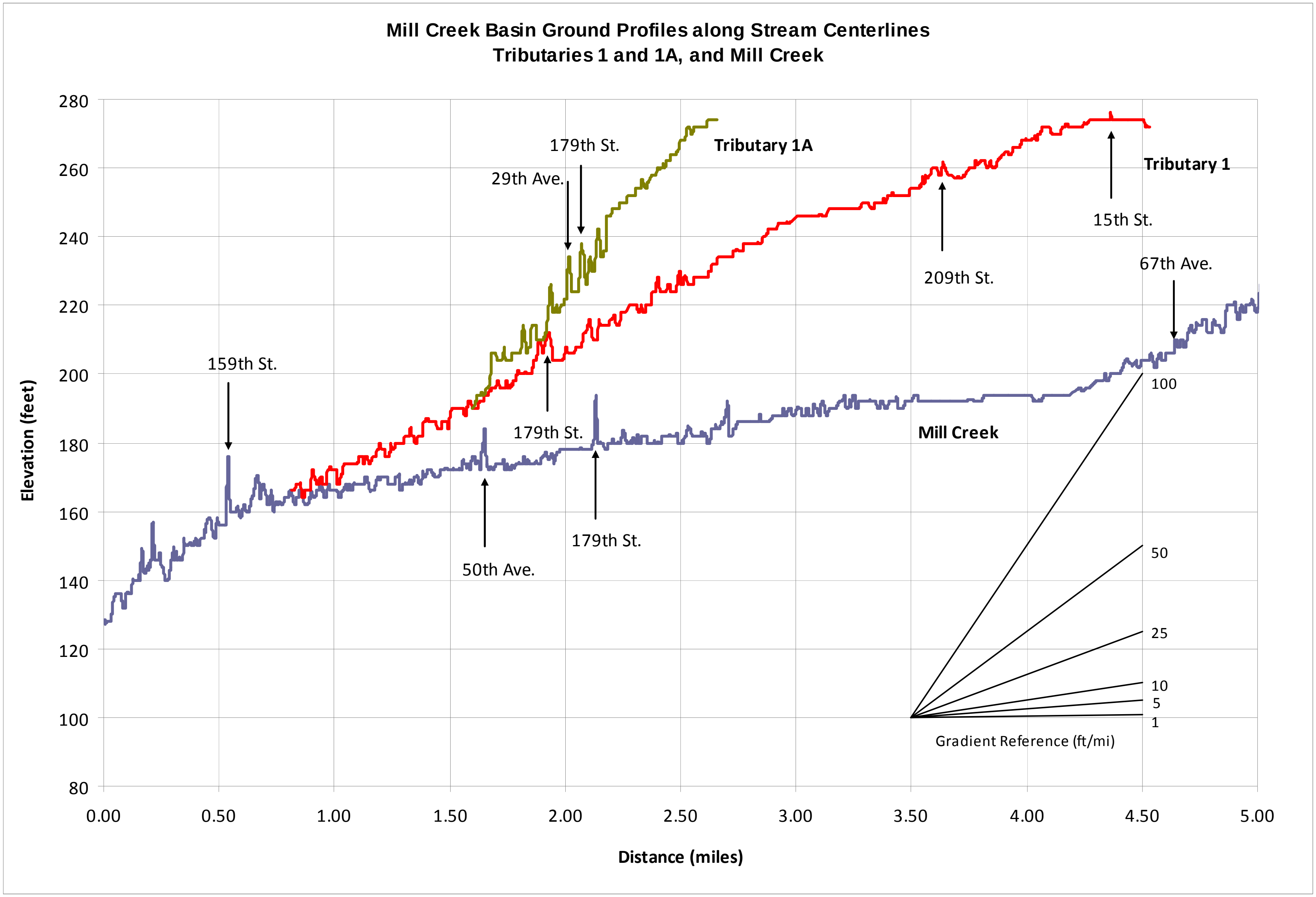


**Figure 16. Ground profiles along Tributaries 1 and 1A, and Mill Creek.**

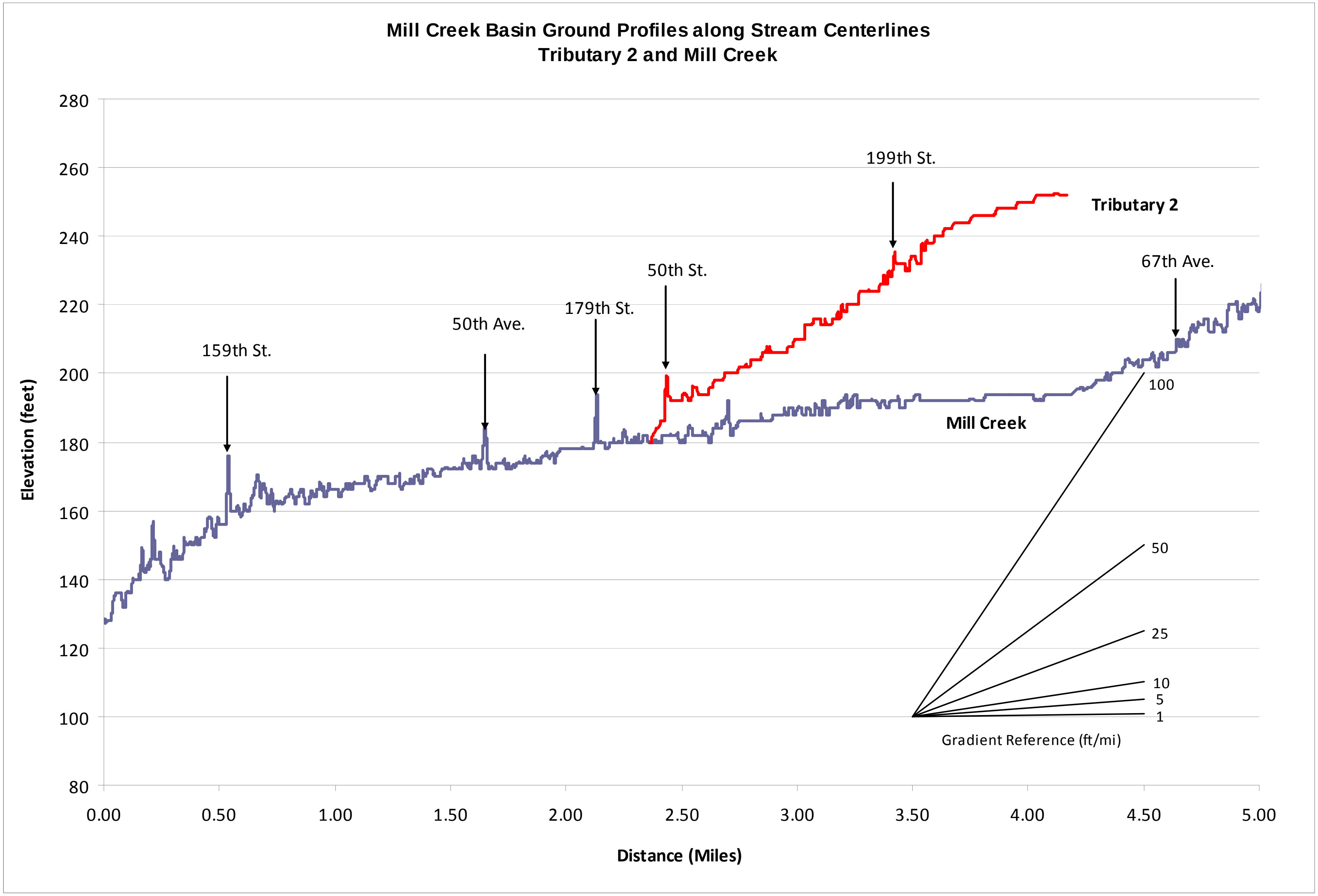


**Figure 17. Ground profiles along Tributary 2 and Mill Creek.**

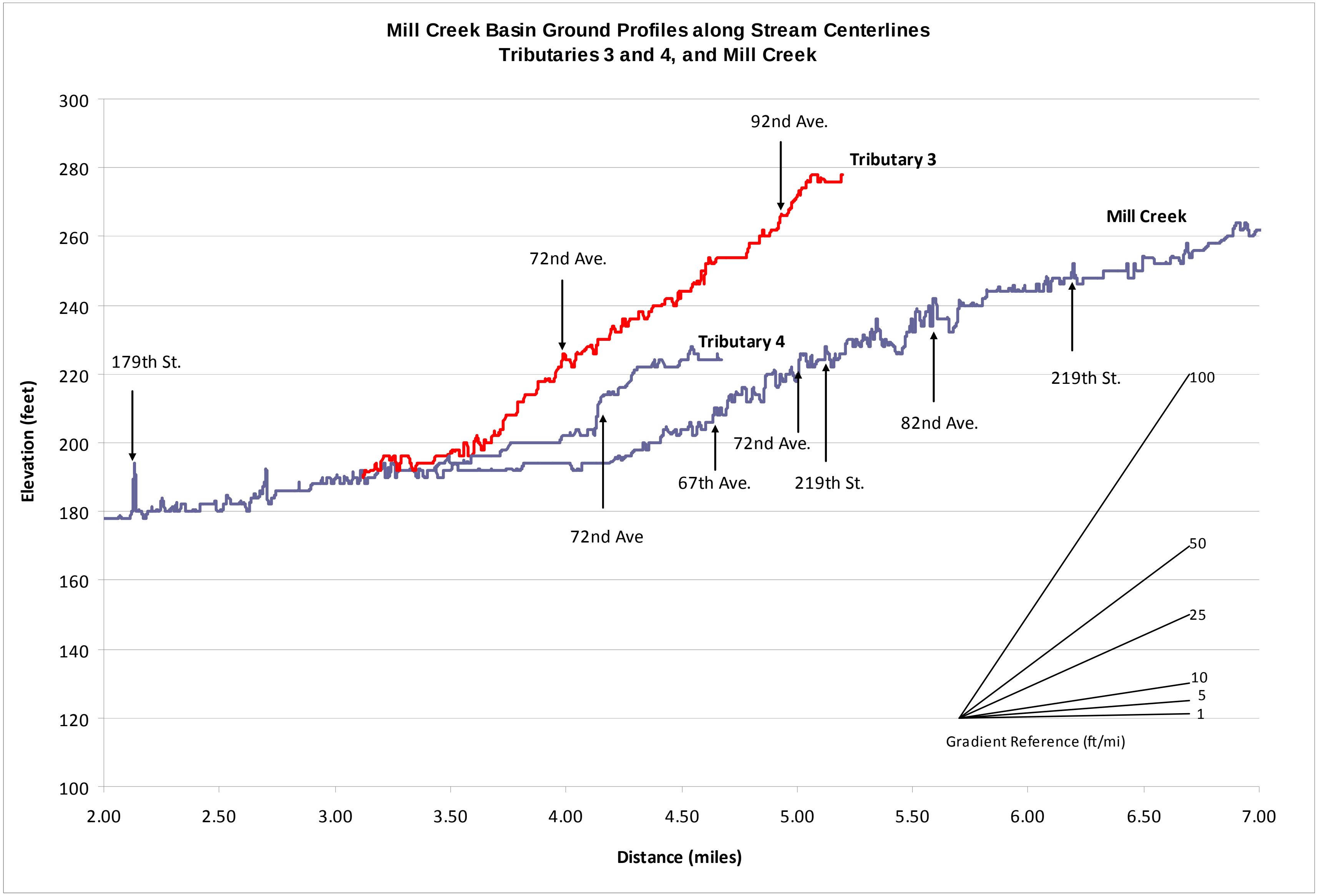


**Figure 18. Ground profiles along Tributaries 3 and 4, and Mill Creek.**

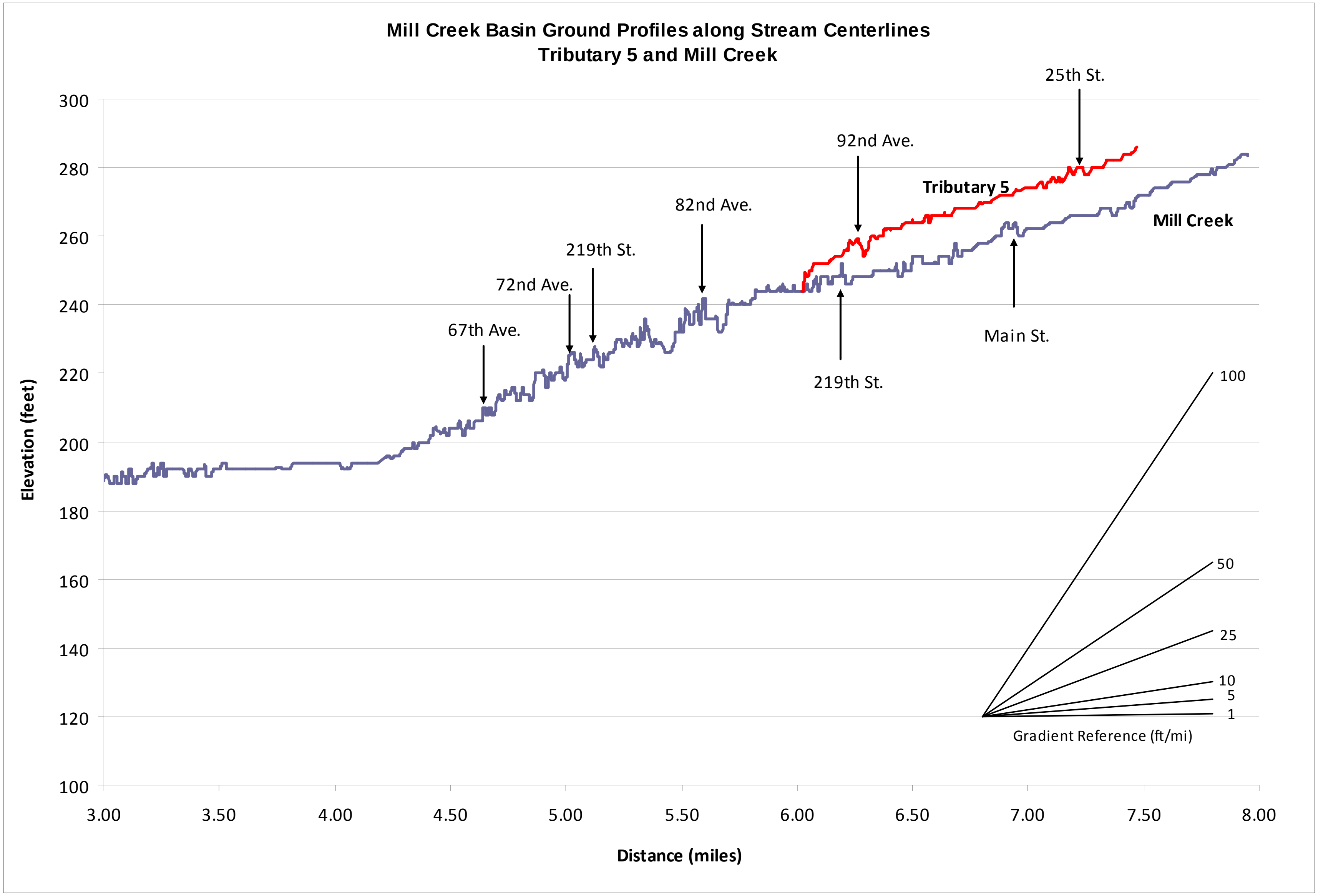


**Figure 19. Ground profiles along Tributary 5 and Mill Creek.**

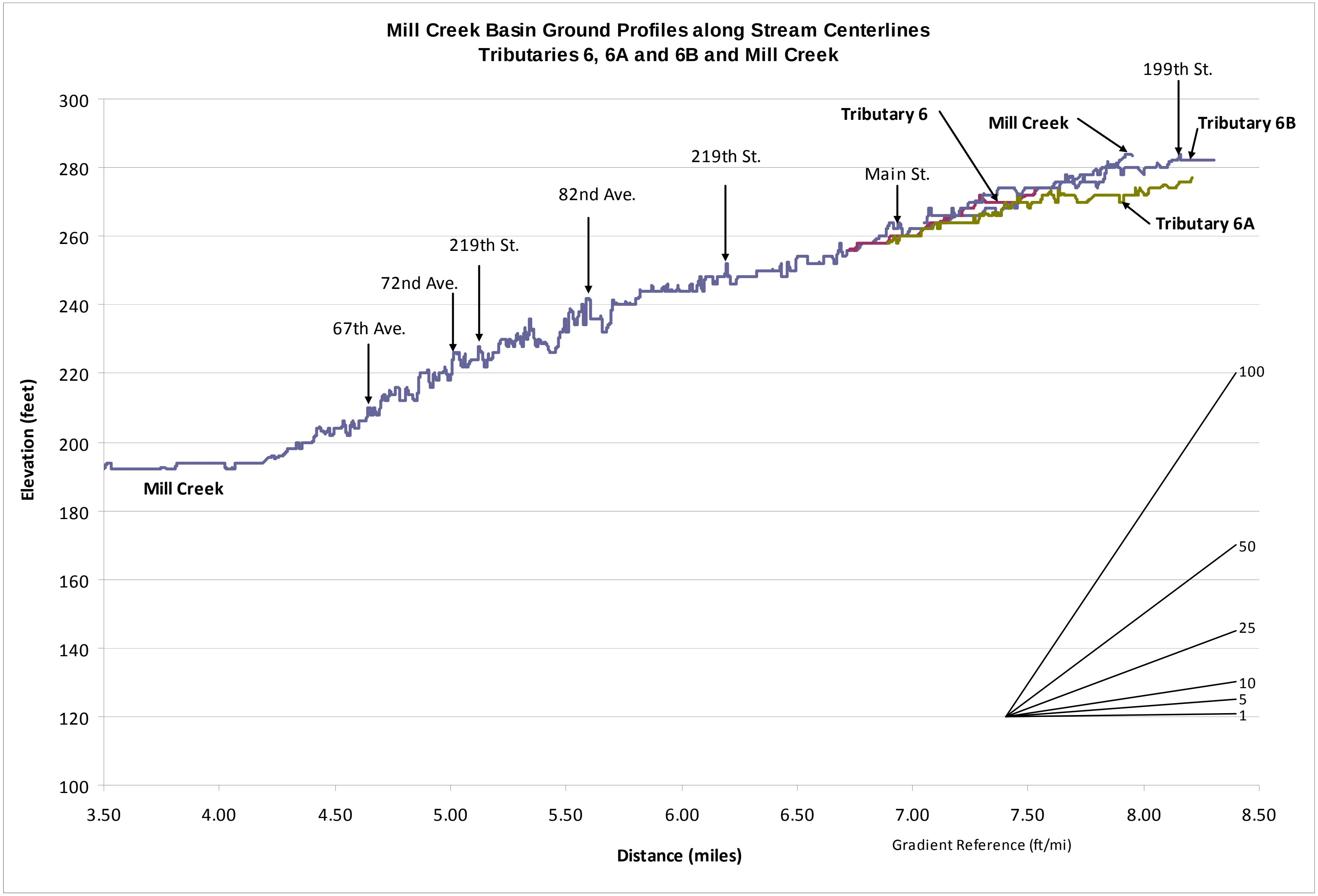


**Figure 20. Ground profiles along Tributaries 6, 6A and 6B and Mill Creek.**

### 3.3.2 Channel Planform

#### 3.3.2.1 Reach 1

Reach 1 extends from the mouth of Mill Creek to just downstream of NE 159th Street. The reach has moderate sinuosity and is fairly steep (S=0.011) compared to the upstream reaches of the creek. Evaluation of the historic map from 1858 (BLM, 2008) (Figure 6) indicates that the confluence of Mill Creek with Salmon Creek was located approximately 2,300 feet further to the southwest and that Salmon Creek was located approximately 1,500 feet further to the south. It appears that Salmon Creek migrated to the north, converged with Mill Creek, and created a new confluence and thus abandoned the portion of the channel between the new confluence and the previous confluence (see Figure 21). The convergence of the creeks likely resulting in headcutting along Mill Creek which would account for the relatively steep gradient and incised channel form within Reach 1. It should be noted that topographic data (Clark County, 2003) indicate that the location of the 1858 Salmon Creek channel shown in Figure 21 may not be correct. The ground elevations in the area of Pleasant Valley School are significantly higher (~60 feet) than the current channel and floodplain elevations of Salmon Creek suggesting that Salmon Creek was incorrectly located on 1858 map.

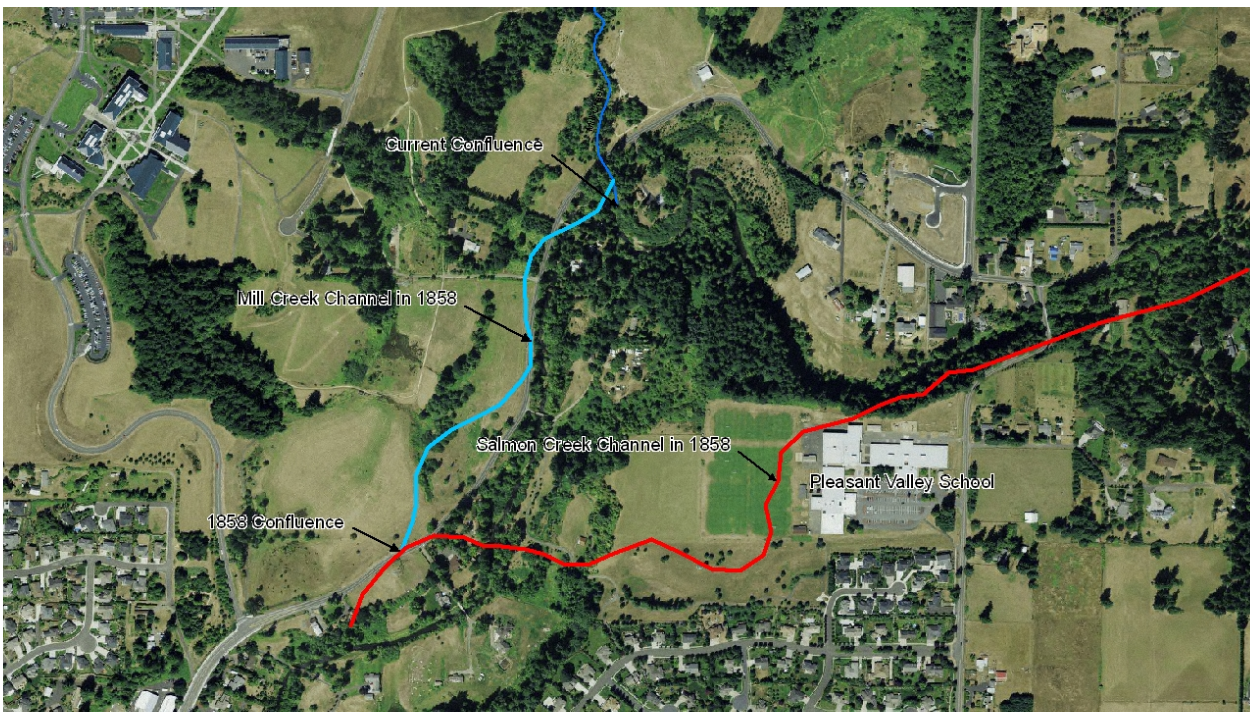


**Figure 21. Confluence of Mill Creek with Salmon Creek showing approximate location of channels in 1858.**

The bed material in Reach 1 has a median diameter of 1.2 inches (30 mm) which is classified as coarse gravel. The maximum particle size is 3 inches (76 mm) which is classified as small cobble. This material is derived from the underlying coarse grained Troutdale Formation and is not readily transportable except during significantly high flows.

Except for the depositional zone near the confluence with Mill Creek, Reach 1 is considered a supply limited "source" reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. Channel incision is occurring but is hindered by the erosion resistance of the coarse grained bed material. Bank erosion and bank failures are occurring along the outside of meander bends and where flows are locally impinging on the bank. Reach 1 is contained nearly entirely within the WSU campus which is devoid of significant development near the channel. However, stormwater runoff from the campus is conveyed to Mill Creek.

#### 3.3.2.2 Reach 2

Reach 2 extends from just downstream of NE 159th Street to approximately RM 2.8. The reach has low sinuosity and has a mild slope (S=0.002). The bed material in Reach 2 is somewhat finer than in Reach 1 and has a median diameter of 0.5 inches (13 mm) which is classified as medium gravel. The maximum particle size is 2 inches (51 mm) which is classified as very coarse gravel. Although not shown on the geologic map, the bed material is derived from the underlying coarse grained Troutdale Formation and is not readily transportable except during significantly high flows. The break in gradient between Reach 1 and Reach 2 is likely the result of a transition between a more erosion resistant layer composed of coarse grained gravel in Reach 1 and a somewhat less erosion resistant layer composed of the medium grained gravel in Reach 2.

Similar to Reach 1, Reach 2 is considered a supply limited “source” reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. Further, because the coarse grained bed material is not readily transportable, it provides some resistance to channel incision. Reach 2 is generally surrounded by rural residential and agriculture areas with minimal encroachment into the riparian zones.

#### 3.3.2.3 Reach 3

Reach 3 extends from approximately RM 2.8 to approximately RM 4.2. Except for some localized stream restoration that included remeandering of the channel, the channel is nearly straight and appears to have been channelized at some point in the past. Reach 3 has the flattest gradient compared to other reaches along Mill Creek with a slope of 0.0009. As seen in Figure 1, Reach 3 is underlain by the coarse grained Troutdale Formation. However, because of the very flat gradient, the bed material consists of sand and silt sized material which is derived from upstream sources.

As seen in Figure 6, the upper end of Reach 3 passes through an area that was historically classified as wetland (BLM, 2008) and may not have contained a channel prior to Euro-American settlement. As previously mentioned, there is a bifurcation of flow just below the upstream end of Reach 3 at the point where the channel turns from west to south. Flow is split at this location, flowing both to the north into the Mill Creek East Fork Lewis River Tributary and to the south into Reach 3 of Mill Creek.

In contrast to both downstream and upstream reaches, this reach is considered a transport limited “deposition” reach in that sediment supply generally exceeds sediment transport capacity. Because this reach has a fairly flat gradient sediment deposition is occurring. However, the fine-grained nature of the inflowing sediment allows it to be transported as suspended load. Therefore, the majority of sediment deposition likely occurs in the extensive floodplain areas adjacent to both channel banks. When flows are confined to the channel, the uniform trapezoidal cross section geometry and nearly straight alignment of the channel results in a greater ability to transport sediment which tends to limit sediment deposition within the channel. There is not sufficient energy to erode the channel banks, therefore the development of a meandering planform is not expected.

Reach 3 is generally surrounded by rural residential and agriculture areas with significant encroachment into the riparian zones. Much of the riparian areas have been disturbed by agricultural practices. However, a large portion of the riparian corridor between NE 199th Street and the downstream limit of Reach 3 has been replanted as part of a restoration project and should be provide improved function as the vegetation matures.

#### 3.3.2.4 Reach 4

Reach 4 extends from approximately RM 4.2 to NE 219th Street (RM 6.2). The reach has low sinuosity and has a moderately steep slope (S=0.005). The bed material in Reach 4 is fairly coarse and is similar to the bed material found in Reach 1. The median diameter of the bed material ranges from 1.0 inch (26 mm) near the upstream end of the Reach to 1.6 inches (40 mm) near the downstream end of the reach. Material with these sized characteristics is classified as coarse gravel and very coarse gravel, respectively. The maximum particle size ranges from 3 inches (76 mm) near the upstream end of the reach to 4 inches (101 mm) near the downstream end of the reach. Material with these sized characteristics is classified as small cobble. Similar to Reaches 1 and 2, the bed material is derived from the underlying coarse grained Troutdale Formation and is not readily transportable except during significantly high flows.

Except for the depositional zone near the transition between Reach 4 and Reach 3 located just downstream of NE 76th Avenue, Reach 1 is considered a supply limited “source” reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. Channel incision is occurring but is hindered by the erosion resistance of the coarse grained bed material. Bank erosion and bank failures are occurring along the outside of meander bends and where flows are locally impinging on the bank.

Reach 4 is generally surrounded by rural residential areas with some commercial and industrial uses near Dollar Corner (intersection of NE 219th Street and NE 72nd Avenue). As a result the riparian corridor tends to be fairly narrow.

#### 3.3.2.5 Reach 5

Reach 5 extends from NE 219th Street to a private driveway bridge located at approximately RM 6.6. The reach has low sinuosity and has a mild slope (S=0.002). The bed material consists of sand and silt which tends to be vegetated with grasses and other wetland vegetation.

Reach 5 is a considered supply limited “source” reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. Channel incision is occurring but is partially limited by the culverts at NE 219th Street and a private driveway. As a result, the channel has become entrenched and disconnected from its floodplain.

Reach 5 is generally surrounded by agricultural areas with significant encroachment into the riparian zones. Much of the riparian areas have been disturbed or are devoid of riparian vegetation as a result of surrounding land use.

#### 3.3.2.6 Reach 6

Reach 6 is a fairly short reach which extends from the private driveway bridge at approximately RM 6.6 to the private driveway bridge at approximately RM 6.9. The reach has low sinuosity and has a moderately steep slope (S=0.007). The bed material consists of sand and silt which tends to vegetated with grasses and other wetland vegetation.

Reach 6 is considered a supply limited "source" reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. Channel incision is occurring but to a lesser degree than Reach 5. The channel is disconnected from its floodplain except during extreme flood events.

Reach 6 is surrounded by agricultural areas with significant encroachment into the riparian zones. Much of the riparian areas have been disturbed or are devoid of riparian vegetation as a result of surrounding land use.

#### 3.3.2.7 Reach 7

Reach 7 extends from the private driveway bridge at approximately RM 6.9 to RM 7.6. The reach has low sinuosity and has a moderately steep slope (S=0.004). The bed material consists of sand and silt which tends to vegetated with grasses and other wetland vegetation.

Reach 7 is considered a supply limited "source" reach in that for most flow conditions the channel has the ability to transport more sediment than is supplied to it. As a result, sediment deposition and resulting migration are limited in this reach. The channel is somewhat entrenched downstream of NE 219$^{th}$ Street (Main Street) and then again upstream of NW 20$^{th}$ Avenue where it has been channelized. Between NW 219$^{th}$ Street and NW 20$^{th}$ Ave the channel is well connected to the floodplain but appears to have been modified or relocated based on the nearly straight channel alignment.

Reach 7 is surrounded by agriculture, commercial and urban residential development. Much of the riparian areas have been disturbed or are devoid of riparian vegetation as a result of surrounding land use.

### 3.3.3 Valley Cross Section Geometry

Selected cross sections located along the valley of Mill Creek were extracted from the DTM of the basin to help understand the valley geometry and how its form transitions from upstream to downstream. The locations of the extracted cross sections are shown in Figure 22. Valley cross section geometries are shown in Figure 23.

#### 3.3.3.1 Reaches 1 (cross section 1)

Reach 1 of Mill Creek is located in the transition zone between a moderately deep and narrow valley and the broad valley form of Salmon Creek. As seen in Figure 23, cross section 1 shows two flat surfaces that appear to be abandoned floodplain terraces. Adjacent to the terraces are erosional scarps which likely developed from lateral migration of Mill Creek and/or Salmon Creek. The abandoned floodplain terraces and valley form suggest that the lower portion of Reach 1 has undergone several episodes of deposition and erosion in the past.

#### 3.3.3.2 Reach 2 (cross sections 2 and 3)

Reach 2 of Mill Creek is located within a relatively narrow valley that is between 40 and 60 feet deep with moderately steep valley walls. Valley bottom widths are typically 50 to 100 feet. Floodplains are typically narrow and discontinuous. The relatively steep and narrow geometry is indicative of the valley's long-term tendency toward erosion.

#### 3.3.3.3 Reach 3 (cross section 4)

Reach 3 of Mill Creek is located in Manor Trough, a historic flood channel of the Columbia River, which is a nearly flat bottomed wide valley. As seen in Figure 23, the bottom width of cross section 4 is approximately 1,500 feet wide. Much of the channel along Reach 3 was likely modified or created in an attempt to improve drainage conditions for agriculture. Historic mapping from 1858 (BLM, 2008) shows that the upper portion of Reach 3 was a large wetland with no existing channel.

#### 3.3.3.4 Reaches 4 through 7 (cross section 5, 6, 7, and 8)

Reaches 4 through 7 of Mill Creek are surrounded by relatively flat and unconfined topography. These reaches will tend to incise over time and are considered to be the most susceptible to increases in peak flows and/or increases in the duration of flows that exceed the critical shear stress of the bed material. Gradual incision is expected to continue to occur with time unless there is sufficient grade control from vegetation, woody debris, or the underlying geology. In reaches 4 and 5, where the stream bed material is of sufficient size to inhibit incision, bank erosion will be more prevalent. Culvert crossings will continue to provide a form of grade control, although this is not typically their primary function. Further, significant discontinuities in grade at culvert outlets can have undesirable impacts on fish passage.

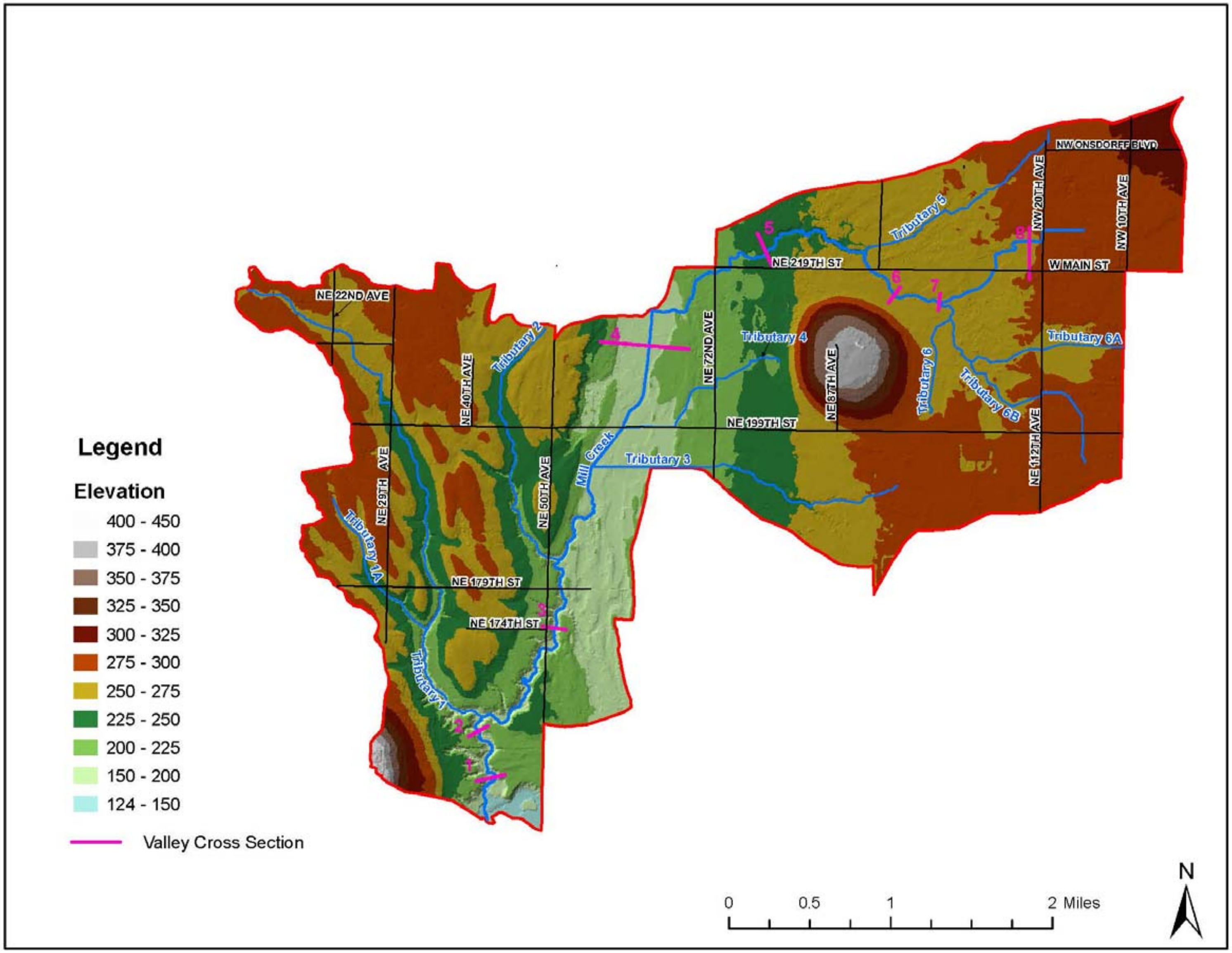


**Figure 22. Location of valley cross section extracted from DTM.**

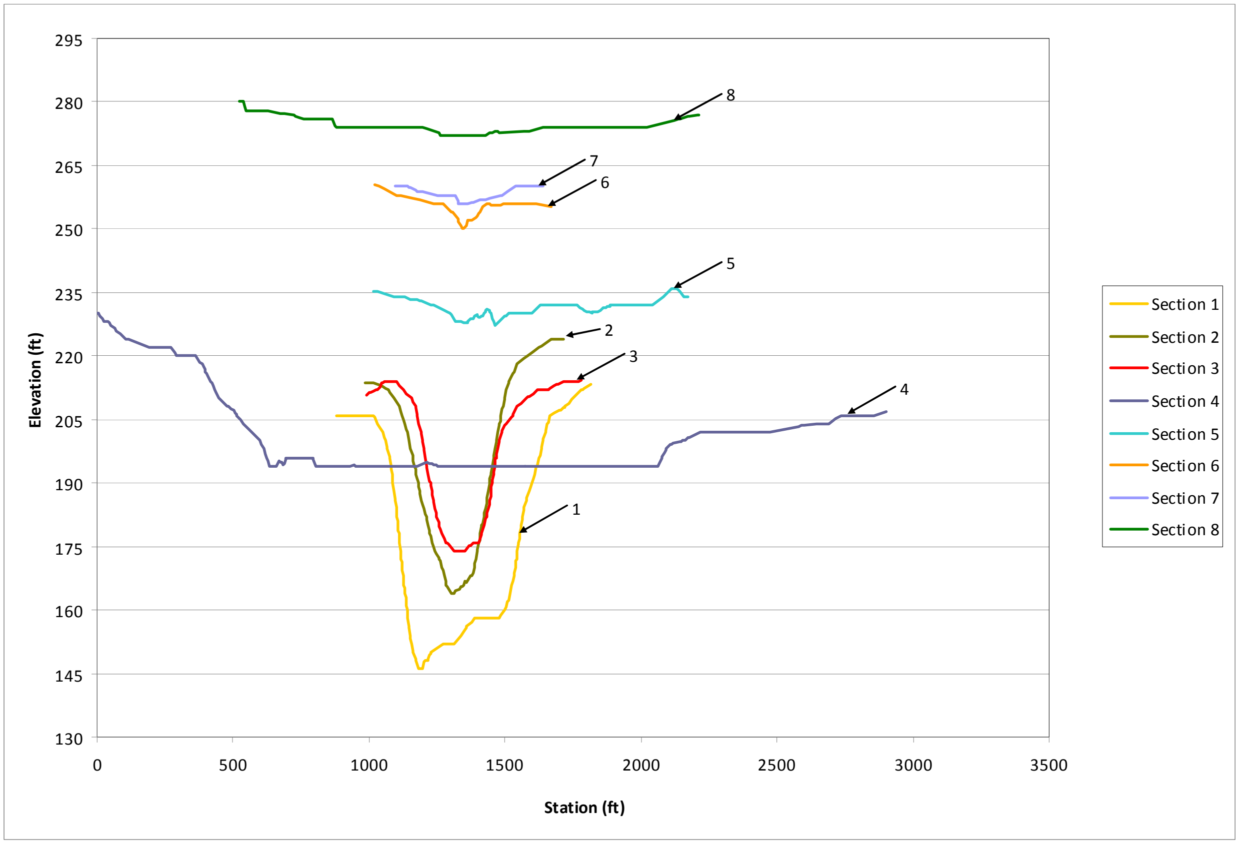


**Figure 23. Valley cross sections for Mill Creek.**

### 3.3.4 Incipient Motion Characteristics

Incipient motion characteristics for Mill Creek were developed from hydraulic model output (WEST, 2008). The results were compared to the bed material sediment size characteristics obtained from bed material samples and observed during the field reconnaissance. Bed material sample locations are shown in Figure 24. The sieve analysis results are shown in Figure 25. As seen in the figure, the bed material sizes are fairly consistent and range from sand (~0.0625 mm) to small cobble (100 mm). The median diameter of the samples ranges from 13 mm to 40 mm (medium to very coarse gravel). The bed material in Reaches 3, 5, 6, and 7 were not sampled as they were observed to consist of sand and silt (<2 mm) which is transportable under most flow conditions unless protected by vegetation. Although not observed, the geologic map (Figure 1) indicates that much of Reach 3 is underlain for coarse grained gravels and cobbles of the Upper Troutdale Formation. The fine sand and silt sized material that forms the bed of the channel is likely a depositional layer resulting for hydraulic conditions in the reach.

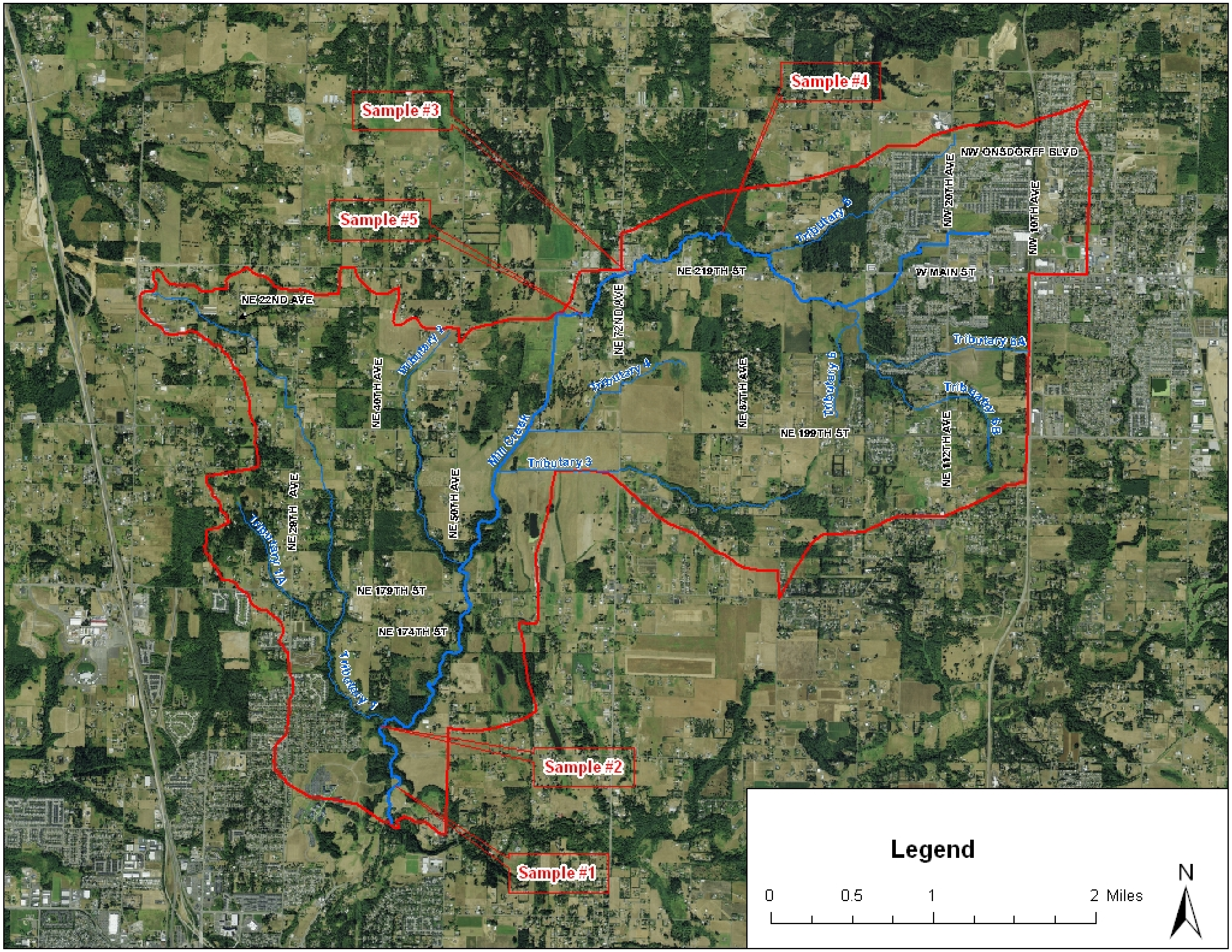


**Figure 24. Bed material sample locations.**

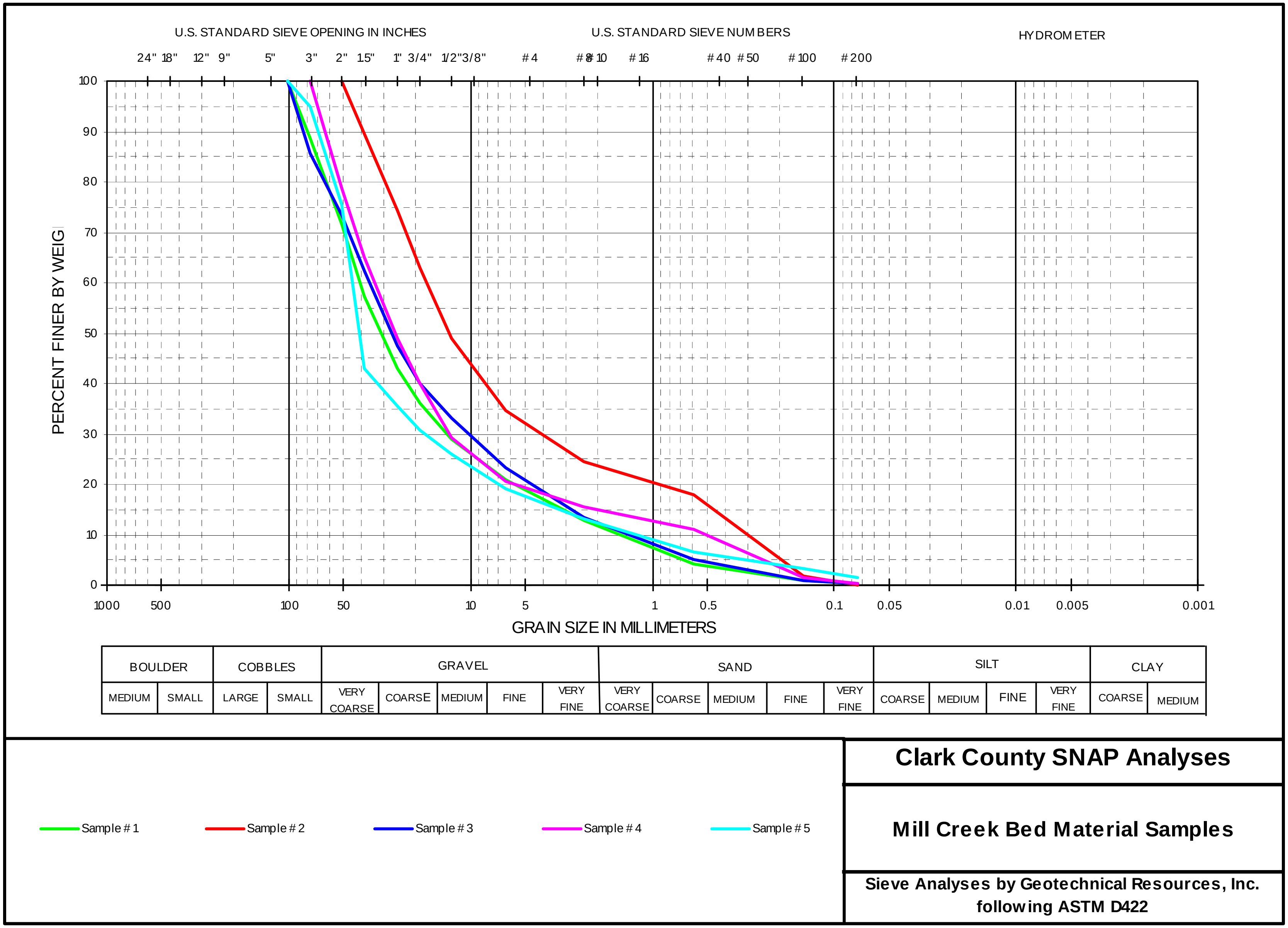


**Figure 25. Bed material gradation curves for Mill Creek.**

The 1.1-year discharge which is approximately equal to 50% of the 2-year discharge for Mill Creek (WEST, 2008), and the 10-year discharge were used to calculate the average incipient motion sediment sizes along Mill Creek using the Meyer-Peter and Muller equation (1948) for the reaches with gravel and cobble sized bed material and Shield's diagram (Vanoni, 1975) for the reaches with sand and silt sized bed material. As seen in Figure 26, Reaches 1, 2, and 4 generally have incipient motion particle sizes that are less than or approximately equal to the median bed material size for the 1.1-year discharge. The bed material would not be expected to be transportable in these reaches for the 1.1-year or smaller discharge. However, Reaches 3, 5, 6, and 7 have incipient motion particle sizes that are greater than the median bed material size. Therefore, the bed material would be expected to be transported for the 1.1-year discharge. However, in these reaches resistance to sediment movement is provided by grassy vegetation that lines much of the channel bed and banks. It should be noted that the incipient motion particle sizes shown in Figure 26, are based on reach averaged hydraulic conditions and that not all locations within a particular reach will be represented by the figure. This is particularly the case at road crossings where the incipient motion particle size decreases upstream of road crossings and increases downstream of road crossing due to local hydraulic conditions associated with the bridge or culvert crossing. It should also be noted that the above discussion of sediment transport potential is based on the bed material size characteristics and does not reflect the potential for erosion of the bank material. Where local hydraulic conditions exceed the sediment transport threshold for the bank material and vegetation or other protection is not provided, bank erosion would be expected to occur.

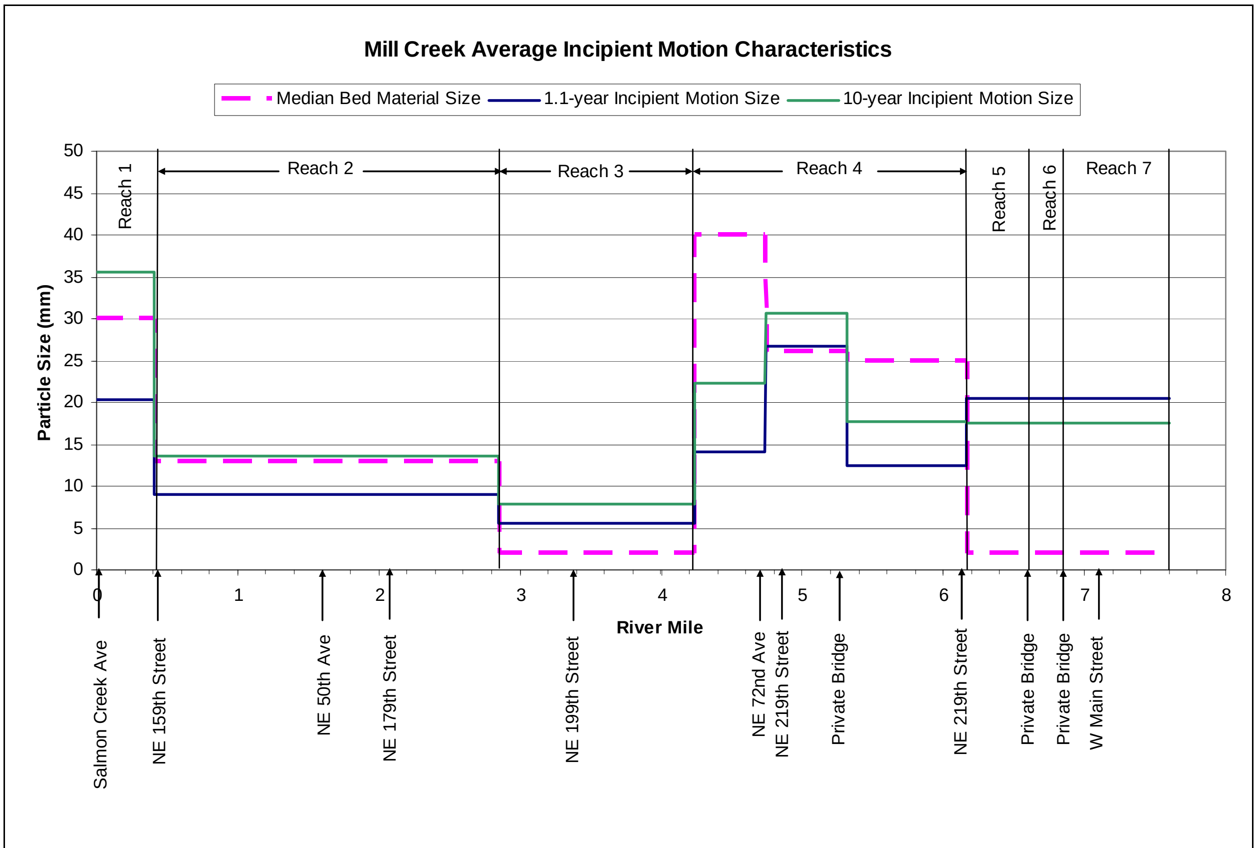


**Figure 26. Incipient motion particle size characteristics for Mill Creek.**

### 3.3.5 Large Woody Debris

Prior to removal, large diameter trees would have provided a supply of large woody debris to the stream channels. Large woody debris likely played a significant role in the form and function of Mill Creek. The size of the channels in the Mill Creek basin are too small to transport the majority of the wood that was contributed by the riparian forests that were once present along the stream corridor. Therefore, if not removed, the large woody debris likely remained in the channels until decay.

Large woody debris provides roughness, helping to dissipate energy and reduces the ability of the stream to transport sediment. Woody debris can also provide a protective cover, essentially shielding the bed and banks from erosive flow conditions. Further, large woody debris can act as grade control locally reducing the channel slope, trapping sediment and preventing channel incision. Woody debris can also control local hydraulic conditions that provide complexity and a variety of habitat conditions.

The majority of the remaining forest land in the Mill Creek basin is found in small patches throughout the basin and intermittently along the fairly narrow riparian corridor of Mill Creek. The extent to which the remaining forest lands have been altered from their conditions prior to Euro-American settlement is unknown. However, field observations indicate that the remaining forest lands do not contain a significant amount of large diameter trees suggesting that much of the original timber was likely harvested in the late 1800's and early 1900's.

### 3.3.6 Conclusions

The mainstem and tributary channels in the Mill Creek basin are currently experiencing significant geomorphic changes resulting from both historic and current land use conditions. The underlying geologic formations in the basin are both controlling the type of changes and limiting the extent of the changes. The coarse grained Upper Troutdale Formation resists channel incision. However, the finer grained soils the form the channel banks are susceptible to erosion where bank protection is not present. The stream reaches located in the upper portion of the basin within the more easily transported fined grained Cataclysmic Flood Deposits are the most susceptible to channel incision but are somewhat protected by vegetation. However, if flow quantities and durations increase in the future, the ability of the vegetation to remain in place will be diminished. As a result, significant changes to channel morphology in the form of channel incision and bank failures would be expected.

Channel reaches that contain sufficient functional large woody debris are less susceptible to degradation by future increases in peak flows and flow durations. Enhancement and/or restoration of native riparian forests will provide a future source of large woody debris to the streams. It is noted that it will take several decades before restored riparian vegetation can provide significant wood delivery to stream channels; however, interim measures could include strategic placement of large woody debris.

The following sections list specific conclusions regarding the geomorphology of channel reaches located within the Mill Creek basin.

#### 3.3.6.1 Mill Creek Reach 1

- Reach 1 is considered moderately susceptible to future increases in peak flows and/or flow durations. The coarse grained sediment derived from the underlying Upper Troutdale Formation is providing resistance to continued incision but the finer grained bank material is susceptible to erosion at high flows and were local flow impingement occurs. Incipient motion calculations suggest that the bed material is generally stable for the 1.1-year (50% of the 2-year) flow. Observations indicate that bank erosion and bank failures are occurring along the outside of meander bends and where flows are locally impinging on the bank. This condition is expected to continue and be exacerbated by potential future flow increases.

#### 3.3.6.2 Mill Creek Reach 2

- Reach 2 is considered less susceptible to future increases in peak flows and/or flow durations than Reach 1. This reach has a milder slope and less severe hydraulic conditions than Reach 1. Like Reach 1, the coarse grained sediment derived from the underlying Upper Troutdale Formation is providing resistance to channel incision. Incipient motion calculations suggest that the bed material is generally stable for nearly the 10-year flow. Observations suggest that the relatively intact riparian corridor and intermittent deposits of woody debris are helping to increase hydraulic roughness and protect the banks from erosion.

#### 3.3.6.3 Mill Creek Reach 3

- As previously mentioned, Reach 3 is a transport limited reach in that, over the long-term, sediment supply generally exceeds sediment transport capacity and given the fine-grained nature of the sediment load, the majority of sediment is carried as suspended load and deposited in the floodplain. Incipient motion calculations suggest that the bed material is not stable for the 1.1-year (50% of the 2-year) flow. However, channel and bank vegetation are providing protection from erosion. The flat gradient, wide floodplain and channelized nature of the stream make this reach the least susceptible to potential future increases in peak flows and/or flow durations.

#### 3.3.6.4 Mill Creek Reach 4

- Reach 4 exhibits similar geomorphic characterizes to Reach 1. It is considered moderately susceptible to future increases in peak flows and/or flow durations. The coarse grained sediment derived from the underlying Upper Troutdale Formation is providing resistance to continued incision but the finer grained bank material is susceptible to erosion at high flows. Incipient motion calculations suggest that the bed material is generally stable for the 1.1-year (50% of the 2-year) flow. Bank erosion and bank failures are occurring along the outside of meander bends and where flows are locally impinging on the bank. This condition is expected to continue and be exacerbated by future flow increases. Although Reach 4 exhibits similar geomorphic characterizes to Reach 1, future degradation in Reach 4 may be more severe than Reach 1 as a result of continued development in the upper basin and lack of upstream floodplain and wetland storage.

- Existing culvert crossings will continue to provide an additional measure of grade control and will limit channel migration within this reach.

### 3.3.6.5 Mill Creek Reach 5, 6 and 7

- Reach 5 through 7 are located within the finer grained Pleistocene Cataclysmic Flood Deposits which makes these streams susceptible to channel incision and bank failures as a result of future increases in peak flows and/or flow durations. Incipient motion calculations suggest that the bed material is not stable for the 1.1-year (50% of the 2-year) flow. Some resistance to erosion is provided by vegetation along the bed and banks but if flow quantities and durations increase in the future, the ability of the vegetation to remain in place will be diminished. As a result, significant changes to channel morphology in the form of channel incision and bank failures would be expected.

- The relatively narrow and often nonexistent riparian corridor will provide little protection from erosive flows and will not provide a supply of large woody debris to the channel.

- Existing culvert crossings will continue to provide a measure of grade control and will limit channel migration within these reaches.

### 3.3.6.6 Tributaries 1, 1A, and 2

- Tributaries 1, 1A, and 2 are located in within finer grained Pleistocene Cataclysmic Flood Deposits which makes these streams susceptible to channel incision and bank failures as a result of future increases in peak flows and/or flow durations. The portions of the tributary basins located south of NE 199th Street are zoned for urban development and if not mitigated would be expected to experience additional impacts to future hydrologic conditions resulting from build out of the current comprehensive plan and zoning. As a result, significant changes to channel morphology in the form of channel incision and bank failures would be expected.

### 3.3.6.7 Tributaries 3 and 4

- Tributaries 3 and 4 are located within finer grained Pleistocene Cataclysmic Flood Deposit which makes these streams susceptible to channel incision and bank failures as a result of future increases in peak flows and/or flow durations. However, these basins are generally zoned for Rural and Agricultural development. Therefore, significant changes to peak flows and/or flow durations are not expected to occur. As a result, significant changes to channel morphology are not anticipated. However, these tributaries currently lack adequate riparian vegetation which may contribute to accelerated rates of bank erosion.

### 3.3.6.8 Tributaries 5, 6, 6A, and 6B

- Tributaries 5, 6, 6A and 6B are located within finer grained Pleistocene Cataclysmic Flood Deposits which makes these streams susceptible to channel incision and bank failures as a result of future increases in peak flows and/or flow durations. The majority of the land within these basins is zoned for urban development and if not mitigated would be expected to experience impacts to future hydrologic conditions resulting from build out of the current comprehensive plan and zoning. As a result, significant changes to channel morphology in the form of channel incision and bank failures would be expected.

### 3.3.7 Recommendations

- Restore and/or enhance riparian vegetation to provide a future source of large woody debris to the channel. Priority should be given to Reaches 5, 6 and 7 and Tributaries 5, 6, 6A, and 6B which are located within areas that have experienced significant urban development and/or are zoned for urban development. These reaches have moderately steep gradients, fine sediments, and higher shear stresses which make them more susceptible to incision.

- Consider placement of large woody debris at strategic locations within in Reaches 1, 4, 5, 6, and 7 and in Tributaries 1, 1A, 2, 5, 6, 6A and 6B. The LWD would dissipate energy and reduce the stream's ability to transport sediment; provide a protective cover to help shield the bed and banks from erosive flow conditions; act as grade control locally reducing the channel slope, trapping sediment and inhibit channel incision; and provide habitat complexity. A thorough hydraulic analysis should be considered to understand the impacts of the LWD placement on water surface elevations and associated flooding conditions.

- Look for opportunities to enhance/expand existing wetlands and floodplains to increase storage of floodwaters and reduce the magnitude and duration of erosive flows.

- Develop incentives that encourage land owners to enhance or restore riparian corridors.

- Develop education and outreach programs that promote the benefits of healthy riparian corridors. Encourage farm and ranch owners to participate in the NRCS Conservation Reserve Program http://www.nrcs.usda.gov/programs/crp/ which is administered through the Clark Conservation District http://www.clarkcd.org/

# 4 Summary and Conclusions

The mainstem and tributary channels in the Mill Creek basin are currently experiencing significant geomorphic changes resulting from both historic and current land use conditions. The underlying geologic formations in the basin are both controlling the type of changes and limiting the extent of the changes. The coarse grained Upper Troutdale Formation resists channel incision. However, the finer grained soils the form the channel banks are susceptible to erosion where bank protection is not present. The stream reaches located in the upper portion of the basin within the more easily transported fined grained Cataclysmic Flood Deposits are the most susceptible to channel incision but are somewhat protected by vegetation.

Reach 5 through 7 are considered the most susceptible to channel incision and bank failures as a result of future increases in peak flows and/or flow durations. These reaches lack a healthy riparian corridor, further reducing the ability of the channel to resist erosion. Some resistance to erosion is currently provided by vegetation along the bed and banks but as flows increase in the future, the ability of the vegetation to remain in place will be diminished. As a result, significant changes to channel morphology in the form of channel incision and bank failures would be expected.

The flat gradient, wide floodplain and channelized nature of the stream along Reach 3 makes this reach the least susceptible to future increases in peak flows and/or flow durations. Prior to channelization, this reach would have provided significant storage and attenuation of floodwaters that would help reduce flows to downstream reaches. The history of this reach as a natural wetland combined with the extensive floodplain area and lack of existing development provide opportunities for floodplain and wetland enhancements as well as stormwater treatment and detention.

Reach 2 is considered moderately susceptible to future increases in peak flows and/or flow durations. The coarse grained sediment derived from the underlying Upper Troutdale Formation is providing resistance to channel incision. The relatively intact riparian corridor and intermittent deposits of woody debris are helping to increase hydraulic roughness and protect the banks from erosion.

Because of its steeper gradient, Reach 1 is considered slightly more susceptible to future increases in peak flows and/or flow durations than Reach 2. The coarse grained sediment derived from the underlying Upper Troutdale Formation is providing resistance to continued incision but the finer grained bank material is susceptible to erosion during high flows. The more severe hydraulic conditions result in increased bank erosion and bank failures along the outside of meander bends and where flows are locally impinging on the bank. This condition is expected to continue and be exacerbated by potential future flow increases.

Various alternatives exist to help protect the streams in the Mill Creek basin from human-caused degradation. The most effective alternatives are to protect and restore riparian forest cover, protect and restore wetlands, limit the increase in effective impervious area, and properly manage runoff associated with development. Current land use zoning maps indicate that 59 percent of the basin can be used for agriculture, parks and open space, and rural residential development. These land uses are likely to produce the least impact to streams compared to the current conditions. The remaining 41 percent is zoned for a mix of low and medium density residential, light industrial, employment center and commercial use, which would be expected to have greater proportion of impervious area and therefore a greater impact on associated basin streams.

Additional alternatives to limit human-caused degradation of streams in the Mill Creek basin include specific project and management recommendations which are presented in the following sections. Implementation of these projects and management recommendations would help reduce the magnitude of current human caused impairments that have resulted from historic and current land use and minimize future impacts resulting from expected future development within the Mill Creek basin.

# 5 Project Recommendations

Various potential projects could be developed to help recover existing impairments and help prevent or reduce future degradation of streams in the Mill Creek basin. Table 8 summarizes the location and types of projects recommended.

**Table 8. Recommended Stormwater Capital Improvement Projects.**

| Stream | Location/Reach | Impairment | Project |
|---|---|---|---|
| Mill Creek | Salmon Creek Street | Undersized bridge | Bridge replacement |
| Mill Creek | Mill Creek u/s of Salmon Creek Ave on WSU campus (Reach 1) | Channel is incised and disconnected from the floodplain resulting in significant bank failures and bank erosion | Grade Control, Floodplain Reconnection, LWD placement, Channel Restoration, Riparian Plantings |
| Mill Creek | 50th Ave | Undersized culvert resulting in backwater | Culvert replacement |

| | | | |
|---|---|---|---|
| | | and excessive downstream scour | |
| Mill Creek | 1,000 feet u/s of 50th Ave | Undersized culvert causing excessive backwater | Culvert replacement |
| Mill Creek | 179th Street | Undersized culvert resulting in backwater and excessive downstream scour | Culvert replacement |
| Mill Creek | u/s from 179th Street to ~1500 ft u/s of 179th Street | Poor riparian cover along left bank. Blackberry are encroaching on channel | Riparian Plantings, Blackberry Removal |
| Mill Creek | Mill Creek at private driveways ~2000 ft u/s of NE 179th Street | Culverts and bridge were not visited during field reconnaissance but are seen to be significantly undersized in existing hydraulic model | Culvert and bridge replacements |
| Mill Creek | Between 199th Street and d/s end of Reach 3 | Portion of channels has been restored but additional portions are still straight oversized ditches | Channel and floodplain restoration |
| Mill Creek | 199th Street | Culvert is undersized resulting in significant backwater conditions that extend ~4,000 feet u/s | Culvert replacement |
| Mill Creek | Between 199th Street and NE 67th Ave | Channelized section is nearly straight ditch that is draining historic wetland areas | Channel and wetland restoration |
| Mill Creek | Between 67th Ave and NE 219th Street just west of 92nd Ave | Channel is entrenched with little or no floodplain connectivity and has intermittent eroding banks. There are a significant number of private culverts and bridges that create excessive backwater conditions and scour conditions. Blackberry are established on the banks and low benches | Grade control, floodplain reconnection, LWD placement, bridge/culvert replacements and blackberry removal |
| Mill Creek | Between Main Street in Battleground and NE 219th Street just west of 92nd Ave | Poor or nonexistent riparian buffer | Riparian plantings, LWD placement |
| Mill Creek | From just d/s of NW 20th Ave in Battleground to ~1300 ft u/s of NW 20th Ave | Poor riparian buffer, channel is a straight and deep ditch | Riparian plantings, floodplain reconnection, channel restoration, LWD placement |
| Tributary 2 | 50th Ave | Culvert is undersized resulting in excessive velocities and a large scour hole downstream of outlet. Inlet is also poorly aligned with flow. | Culvert replacement |

| | | | |
|---|---|---|---|
| Tributary 2 | 199th Street west of 50th Ave | Culvert is undersized resulting in excessive velocities and a large scour hole downstream of outlet. Sedimentation occurring u/s. | Culvert replacement |
| Tributary 5 | From just downstream of NW 7th St in Battleground to NW 25th Ave | Poor or nonexistent riparian buffer | Riparian plantings |
| Tributary 5 | NW 25th Ave in Battleground | Potential headcut issue may have resulted from construction of adjacent stormwater pond | Grade Control |
| Tributary 5 | From 600 feet d/s to 600 ft u/s of NE 92nd Ave | Narrow riparian buffer | Riparian plantings |
| Tributary 5 | NW 92nd Ave | Culvert is too short and has a failed joint causing embankment failures at u/s and d/s ends | Culvert replacement |
| Tributary 6A | From SW 20th Ave to SW 10th Ave | Poor or nonexistent riparian buffer, recently excavated ditch in adjacent field contributing fine sediment to channel. | Riparian Plantings, Sedimentation Pond or Filter Fences or other appropriate BMP's |
| Tributary 6A | From 250 d/s of SW 24th Ave to 1000 u/s of SW 24th Ave | Poor to moderate riparian buffer | Riparian plantings |
| Tributary 3 | From NE 72nd Ave to confluence with Mill Creek (~4,000 ft) | Poor riparian buffer, channel is a straight and deep ditch | Riparian plantings, floodplain reconnection, channel restoration |

As seen in Table 8, multiple culverts along Mill Creek should be replaced. The hydraulic model for Mill Creek (WEST, 2008) indicate that these culverts are undersized resulting in significant backwater and in some cases roadway overtopping during less than a 10-year recurrence interval flood. These culverts should be replaced with a hydraulic structure that accommodates natural fluvial processes and does not significantly alter the hydraulic and sediment transport characteristics of the channel. Potential upstream and downstream impacts resulting from the replacement structure and mitigation for these impacts must be considered during design.

Varies reaches of Mill Creek and several tributaries have been significantly altered to improve drainage of surrounds lands. These areas could be restored to improve floodplain and wetland connectivity to help provide storage and attenuation of flood waters as well as improved wetland and riparian habitat.

The remaining recommended projects are either enhancement or establishment of a healthy riparian corridor through invasive species removal and new riparian plantings. These types of projects are considered to provide the greatest benefit to the streams in the Mill Creek basin. From a geomorphic standpoint, an established riparian corridor will help create hydraulic roughness that reduces stream velocities and erosion potential and help reduce bank erosion. More importantly it allows for future recruitment of large woody debris which is generally lacking in the basin streams. An established functional riparian corridor will help minimize impacts associated with future increases in flow magnitudes and/or durations.

# 6 Management Recommendation

Various management alternatives exist to help recover existing impairments and reduce future degradation of streams in the Mill Creek basin:

- Develop projects that restore the hydrologic and habitat functions of areas that historically were considered wetlands. Specifically, wetland restoration projects located within the wide valley bottom containing Mill Creek located between NE 67th Ave and the confluence of Tributary 3 which is located just south of NE 199th Street. Figure 6 indicates that there may be additional opportunities for wetland restoration projects within the subbasin of Tributary 6. These projects would help protect the middle and lower reaches of Mill Creek by helping reduce future increases in erosive flows.

- It is noted that the land use zoning map provides a broad level of detail regarding land use for a 20-year period (2004-2024). Those portions of the basin that are expected to experience the least amount of development over this time period should not be ignored. Reestablishment of riparian corridors along the middle portion of Mill Creek will provide greater protection to the stream channel as development pressure in the upper portion of the basin increases in the future.

- Dams and associated ponds should be individually evaluated to determine the impact each is having on the hydrology, water quality and geomorphology of the involved stream. This could be used to prioritize both modifications to and/or removal of existing structures.

- Infiltration facilities should be considered the preferred option for disposal of stormwater in areas where site specific soil and groundwater conditions are appropriate.

- Existing and future stormwater detention facilities should be evaluated through the use of continuous simulation hydrologic modeling to understand the magnitude of modifications to the duration of flows compared to predevelopment conditions.

- Ensure appropriate BMPs are being implemented with regard to maintenance of drainage ditches and discourage the development of new drainage ditches that have a direct connection to natural channels.

- Use geomorphically based performance standards when designing and constructing new or replacement hydraulic structures at road crossings. Designs should allow for lateral and longitudinal continuity and connectivity of both the channel and functional floodplain in addition to hydraulic design considerations. Potential upstream and downstream impacts resulting from the replacement structure and mitigation for these impacts must be considered during design. Mitigation in the form of woody debris jams and grade control or other appropriate measures should be installed to offset the loss of floodplain connectivity and channel incision that would likely occur as a result of the replacement structure.

- Replace culverts or install energy dissipation devises downstream of culverts where scour has degraded the downstream channel. Culvert crossings at NE 50th Ave, NE 179th Street, NE 199th Street and multiple private culverts are exhibiting these conditions.

- Encourage the use of Low Impact Development (LID) measures for newly developing areas in the basin. LID focuses on minimizing the amount of runoff generated from the site by minimizing to the extent practical the amount of increased impervious surface area and infiltrating and treating stormwater runoff near the source in order to best mimic the predevelopment hydrologic conditions. Where soil conditions are a limiting factor on infiltration, LID practices should be combined with traditional stormwater detention/retention facilities.

- Continue monitoring stream flows at the WSU gage and consider the installation of an additional stream gage in the upper portion of the Mill Creek Basin near Dollar Corner (intersection of NE 219th Street and NE 72nd Avenue). $T_{Qmean}$ and other streamflows statistics can be used to help evaluate the effectiveness of stormwater management practices as future development occurs in the basin. However, flow monitoring at the WSU gage may not capture the extent of hydrologic changes that are occurring in the upper basin. An additional stream flow gage would allow for results that represent the upper portion of the Mill Creek basin and thus exclude the storage and attenuation of flows that occurs between approximately RM 2.8 and RM 4.2 (Reach 3 as described is Section 3.3).

- Conduct periodic updates to the recently developed continuous simulation hydrologic model of the Mill Creek basin to account for land use changes and any constructed regional stormwater facilities. This will provide an appropriate base condition to help evaluate changes in basin hydrology associated with proposed future development. The updated model would also help determine the magnitude and location of expected hydrologic changes and be useful to evaluate the effectiveness of potential stormwater facilities and/or mitigation projects.

- Develop more stringent stormwater flow control regulations that control peak discharges and the duration of erosive flows in order to help protect and restore stream channel and riparian habitat in the Mill Creek basin.

- Where appropriate, develop regional stormwater detention facilities and/or enhance existing wetland and floodplain storage areas to reduce hydrologic impacts to basin stream channels.

- Restore and/or enhance riparian vegetation to provide a future source of large woody debris to the channel. Priority should be given to Reaches 5, 6 and 7 and Tributaries 5, 6, 6A, and 6B which are located within areas that have experienced significant urban development and/or are zoned for urban development. These reaches have moderately steep gradients, fine sediments, and higher shear stresses which make them more susceptible to incision.

- Consider placement of large woody debris at strategic locations within in Reaches 1, 4, 5, 6, and 7 and in Tributaries 1, 1A, 2, 5, 6, 6A and 6B. The LWD would dissipate energy and reduce the stream's ability to transport sediment; provide a protective cover to help shield the bed and banks from erosive flow conditions; act as grade control locally reducing the channel slope, trapping sediment and preventing channel incision; and provide habitat complexity. A thorough hydraulic analysis should be considered to understand the impacts of the LWD placement on water surface elevations and associated flooding conditions.

- Look for opportunities to enhance/expand existing wetlands and floodplains to increase storage of floodwaters and reduce the magnitude and duration of erosive flows.

- Develop incentives that encourage land owners to enhance or restore riparian corridors.

- Develop education and outreach programs that promote the benefits of healthy riparian corridors. Encourage farm and ranch owners to participate in the NRCS Conservation Reserve Program http://www.nrcs.usda.gov/programs/crp/ which is administered through the Clark Conservation District http://www.clarkcd.org/

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# Appendix A
# Summary of Field Observations

| Stream | Location | Hydraulic Structure | Upstream of Road Crossing | | | | | | | | | Downstream of Road Crossing | | | | | | | | | Additional Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Floodplain Connectivity | Sinuosity | Riparian Cover | Bed Material | Bank Material | Woody Debris | Land Use | Active Erosion | Potential SCIP | Floodplain Connectivity | Sinuosity | Riparian Cover | Bed Material | Bank Material | Woody Debris | Land Use | Active Erosion | Potential SCIP | |
| Mill Creek | Salmon Creek Street | bridge | poor | moderate | moderate | gravel/cobble | silt/sand/ gravel | no | campus | yes | riparian plantings, grade control, floodplain reconnection | moderate | moderate | good | gravel/cobble | silt/sand/ gravel | minor | rural residential | yes | replace bridge | Extensive channel degradation in this reach. Significant contract scour beneath and d/s of bridge |
| Mill Creek | between Salmon Creek St and 159th Street (WSU campus) | n/a | poor | moderate | moderate | gravel/cobble | silt/sand/ gravel | minor | campus | yes - degradation and bank failures | riparian plantings, grade control, floodplain reconnection | poor | moderate | moderate | gravel/cobble | silt/sand/ gravel | yes | campus | yes - degradation and bank failures | riparian plantings, grade control, floodplain reconnection | |
| Mill Creek | 159th Street | arch culvert | moderate | moderate | good | gravel/cobble | silt/sand/ gravel | yes | campus | no | blackberry removal | moderate | moderate | good | gravel/cobble | silt/sand/ gravel | yes | campus | yes-scour | possible scour mitigation | Large scour hole below culvert - may be left over from previous hydraulic structure |
| Mill Creek | 50th Ave | culvert | good | moderate | moderate - new plantings becoming established - some beaver damage | sand | sand/silt | yes | rural residential | yes - along right bank at culvert entrance | culvert replacement | good | high | good - some blackberry | gravel | silt/sand | yes | rural residential | yes-scour at culvert outlet | replace culvert, blackberry removal | |
| Mill Creek | 179th Street | culvert | good | moderate | poor | silted gravel | silt/sand | no | rural residential | no | blackberry removal/ riparian plantings | moderate | moderate | good | gravel | silt/sand | yes | rural residential | yes-scour at culvert outlet | replace culvert or install energy dissipater | backwater from culvert causing siltation of gravel bed material |
| Mill Creek | 199th Street west of 58th Ave | culvert | moderate | straight | poor | silt/sand | silt/sand | no | rural residential | no | channel restoration/ riparian vegetation | moderate | low | poor - lots of new plantings becoming established | silt/sand | silt/sand | root wads placed along banks | agriculture | no | possible culvert replacement | hydraulic model indicates that culvert is causing moderate backwater impacts |
| Mill Creek | 67th Ave | bridge | poor | moderate | moderate-narrow | gravel/cobble | silt/sand/ gravel | minor | rural residential | minor bank erosion | riparian plantings/ floodplain reconnection | poor | low | poor | gravel/cobble | silt/sand/ gravel | no | rural residential | no | riparian plantings/ floodplain reconnection | |
| Mill Creek | 72nd Ave south of 219th St | bridge | poor | moderate | moderate-narrow | gravel/cobble | gravel/sand/ silt | no | commercial | no | blackberry removal | poor | moderate | moderate-narrow | gravel/cobble | gravel/sand/ silt | no | commercial | minor bank erosion | blackberry removal | stream has been encroached on by commercial buildings and parking lots. |
| Mill Creek | 79th Ave north of 219th St | culvert | good | moderate | moderate | sand/silt | sand/silt | no | rural residential | no | evaluate removal of dam and pond | poor | moderate | moderate | gravel | sand/silt | yes | rural residential | yes - scour hole at culvert outlet | culvert replacement/ dam removal | Road is acting as dam and ponding Mill Creek. Water quality, quantity, and sediment transport impacts associated with the dam should be evaluated further |
| Mill Creek | 219th St. west of 92nd Ave | culvert(s) 2 | poor | moderate | poor | sand | silt/sand | no | rural residential | yes - left bank protected by riprap | riparian plantings/ floodplain reconnection | poor | moderate | poor | sand/fine gravel | silt/sand | minor | rural residential | yes - scour at culvert outets | riparian plantings/ floodplain reconnection | |
| Mill Creek | 219th St. (W. Main St.) | culvert | good | low | good-narrow | silt/sand/ vegetation | silt/sand/ grass | yes | commercial | no | | good | low | no | silt/sand | silt/sand | no | rural residential | no | riparian plantings | |
| Mill Creek | 112th Ave | culvert | poor | straight | none | silt/sand | silt/sand | no | residential | no | riparian plantings/ floodplain reconnection | poor | straight | none | silt/sand | silt/sand | no | commercial | no | riparian plantings/ floodplain reconnection | |
| Unnamed Tributary to Mill Creek | 92nd Ave north of 219th St | culvert | moderate | low | poor-narrow | silt/sand | silt/sand | no | agriculture | yes - u/s roadway embankment is failing because culvert is too short | culvert replacement | moderate | low | poor-narrow | silt/sand | silt/sand | no | agriculture | yes - d/s roadway embankment is failing because culvert has a failed joint | culvert replacement | |
| Unnamed Tributary to Mill Creek | 50th Ave | culvert | good | moderate | good | silted gravel | silt/sand | yes | rural residential | yes -scour at entrance due to poor culvert alignment | culvert replacement | moderate | moderate | moderate | gravel | silt/sand | yes | rural residential | yes-scour at outlet due to excessive velocities | culvert replacement | backwater from culvert causing siltation of gravel bed material |
| Unnamed Tributary to Mill Creek | 199th Street west of 50th Ave | culvert | good | moderate | moderate - young plantings | silted gravel | silt/sand | yes | rural residential | no | culvert replacement | good | moderate | good | gravel/cobble | silt/sand/ gravel | yes | rural residential | yes - scour at outlet of culvert due to excessive velocities | culvert replacement | backwater from culvert causing siltation of gravel bed material |
| Unnammed Tributary to Mill Creek | NW 7th Street | culverts (4) | moderate | straight | none | silt/sand/ grass | silt/sand/ grass | no | urban residential | no | riparian plantings | moderate | straight | no | silt/sand/ grass | silt/sand/ grass | no | urban residential | no | riparian plantings | ditched channel through residential development |
| Unnammed Tributary to Mill Creek | NW 25th Ave | culvert | good | low | good ~ 75 ft u/s of culvert | silt/sand/ grass | silt/sand/ grass | no | urban residential | small headcut or channel modification u/s of culvert | riparian plantings | poor | straight | none | silt/sand/ grass | silt/sand/ grass | no | urban residential | no | riparian plantings | d/s of road crossing is the channel is ditched through residential development |
| Unnammed Tributary to Mill Creek | 112th Ave between 9th and 10th Streets | culvert | moderate | straight | poor | silt/sand | silt/sand | no | agriculture | no | riparian plantings | moderate | straight | moderate | silt/sand | silt/sand | no | urban residential | no | | recent ditching in agricultural field east of 112th Ave is resulting in a sediment plume entering the stream |
| Unnammed Tributary to Mill Creek | 24th Ave north of 11th Street | box culvert | good | low | moderate | sand/gravel | silt/sand | no | urban residential | no | riparian plantings | good | low | moderate | sand/gravel | silt/sand | no | urban residential | no | riparian plantings | |
| Unnammed Tributary to Mill Creek | 72nd Ave south of 199th St | culvert | unknown | low | moderate - dense low growing vegetation | unknown | unknown | unknown | rural residential | unknown | riparian plantings | poor | straight | poor | sand/silt/ grass | sand/silt/ grass | minor | agriculture | yes - bank erosion | riparian plantings/ floodplain reconnection | |