3 Hydrology

In two previous SSWCP updates (1995 Watershed Master Plan and 2007 Stormwater Comprehensive Plan), the City conducted basin-scale hydrology modeling to generate simulated peak flow rates in all of the city's major watersheds. The 1995 analysis used single-event simulations (Waterworks software) to predict peak flow rates for the 2-, 25-, and 100-year, 24-hour design storms for the objectives of controlling channel erosion, evaluating facility sizing, and recommending facility upgrades. Similarly, the 2007 modeling effort was conducted at the basin scale, but used a continuous precipitation record to predict flow rates and evaluate the capacities of the main conveyance networks throughout the city. The City has made progress in implementing past SSWCP recommendations. The conveyance improvement recommendations from the 2007 Stormwater Comprehensive Plan, not previously addressed, are included in the 2020 CIP.

For the 2020 SSWCP update, hydrologic modeling analyses were focused on the sub-watersheds directly draining to Bellingham Bay for the purpose of establishing design flows for hydraulic conveyance capacity modeling of the drainage systems in those areas (see Chapter 7, Stormwater System Analysis, for details of the conveyance modeling).

The City also maintains a stream gage network and collects both flow and water quality data. The Urban Streams Monitoring Program (USMP) was developed to obtain baseline water quality data for streams in the city and used to detect changes in these streams. The USMP is conducted by the Public Works Operations Division. The City has carried out monthly water quality monitoring of streams since 1990, making the USMP one of the longest-standing status and trends programs in the region. Monitoring currently takes place via monthly grabs at 18 sites, on 10 streams: Whatcom, Hannah, Cemetery, Lincoln, Fever, Padden, Connelly, Chuckanut, Squalicum, and Baker Creeks (see Figure 3-1). USMP annual reports for 2006 through 2015 are maintained on the City's website (https://www.cob.org/services/environment/water-quality/pages/urban-streams-monitoring.aspx). The water quality parameters reported are fecal coliform, dissolved oxygen, temperature, pH, turbidity, and conductivity. Each annual report includes updates of annual flow and water quality data with commentary about stream health.

The purpose of this chapter is to provide an overview of the hydrologic conditions of the streams in Bellingham, and to provide recommendations to close data gaps necessary to upgrade the 2007 hydrologic and hydraulic models for possible use in designing CIP projects and assessing conveyance capacities.

3.1 Flow Monitoring Program

The City collects discharge data from the following five stream flow gage stations, as illustrated in Figure 3-1:

- Chuckanut Creek at Arroyo Park
- Whatcom Creek at Derby Pond
- Whatcom Creek at Dupont

- Padden Creek at Fairhaven Park
- Squalicum Creek at West Street

The City compiles 15-minute stream water level (stage) data at each of the gage stations from which 15-minute discharge data are computed. Daily, monthly, and annual discharge descriptive statistics are calculated. Minimum and maximum flows are recorded, while mean flows are computed. Grades are applied to raw data, depending on the accuracy of the equipment or other environmental causes, including excellent, good, fair, and poor. Data gaps may be due to multiple reasons, such as statistical significance criteria (70 percent statistically significant for daily statistics; 75 percent statistically significant for hourly statistics). The period of record for the flow data used in the following analysis is from 2004 to present-day. Presented in the sections below are updates to the flow data including hydrographs of low, average, and high flows, an analysis of low and high pulse counts (HPCs), and a trend analysis (TQ mean) that evaluates hydrologic response to urbanization.

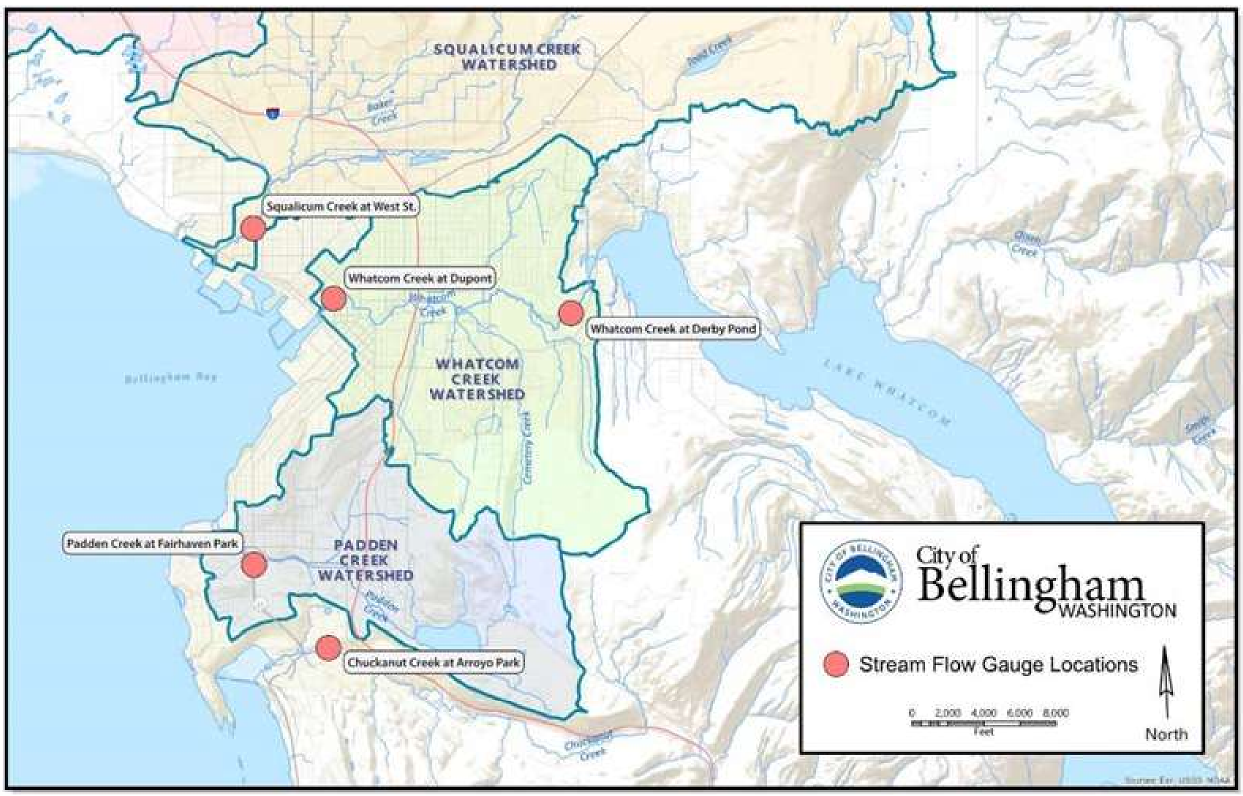

Figure 3-1. City of Bellingham stream flow gage locations

Source: City 2020c.

3.1.1 Flow Data (Average, Low, and High)

Hydrographs of low (10th percentile), high (90th percentile), and average annual flows are presented in this section. Low flows are represented by the 10th percentile flow line, meaning that only 10 percent of the measured flows are below that line, and 90 percent of them are above the value. Conversely, high flows are represented by the 90th percentile flow line, meaning that 90 percent of the measured flows are below the line. Please note differences in scale when comparing graphs between stations. Figure 3-2 through Figure 3-6 show the 10th percentile, average, and 90th percentile annual flows at the respective gage stations.

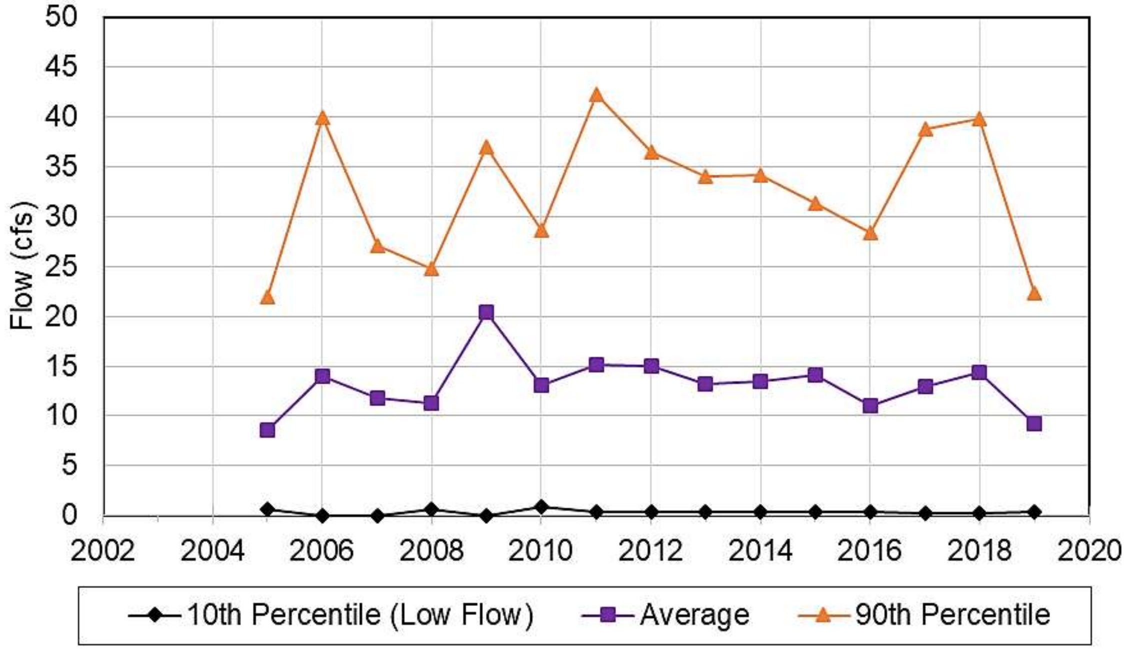

Figure 3-2. Average annual flows Chuckanut Creek at Arroyo Park

Source: City 2020c.

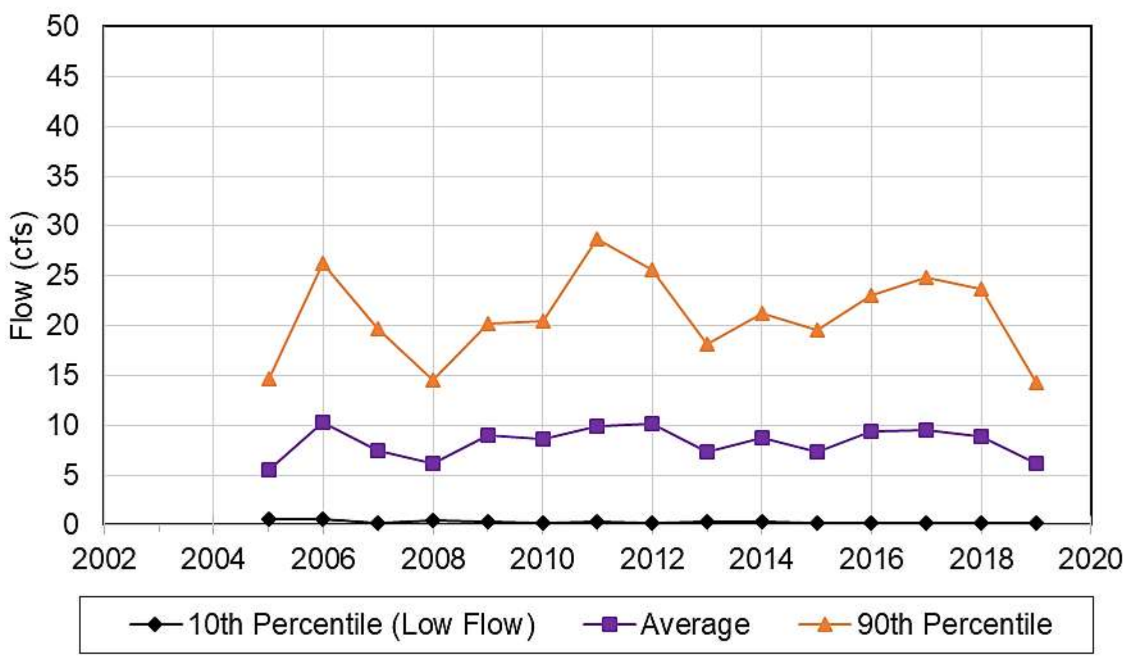

Figure 3-3. Average annual flows Padden Creek at Fairhaven Park

Source: City 2020c.

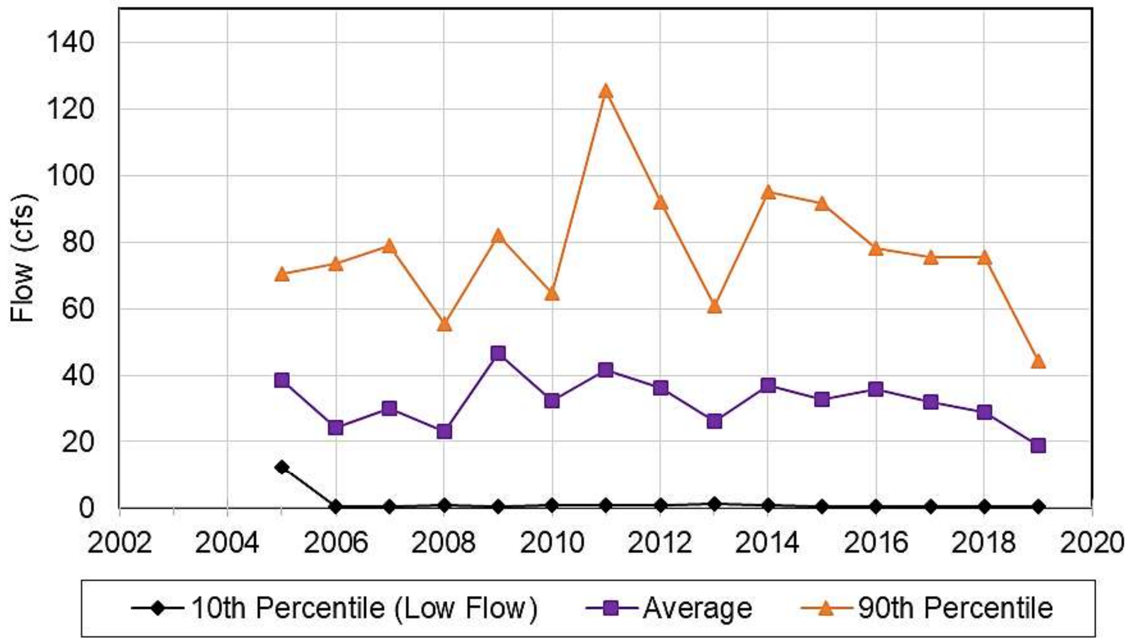

Figure 3-4. Average annual flows Squalicum Creek at West Street

Source: City 2020d.

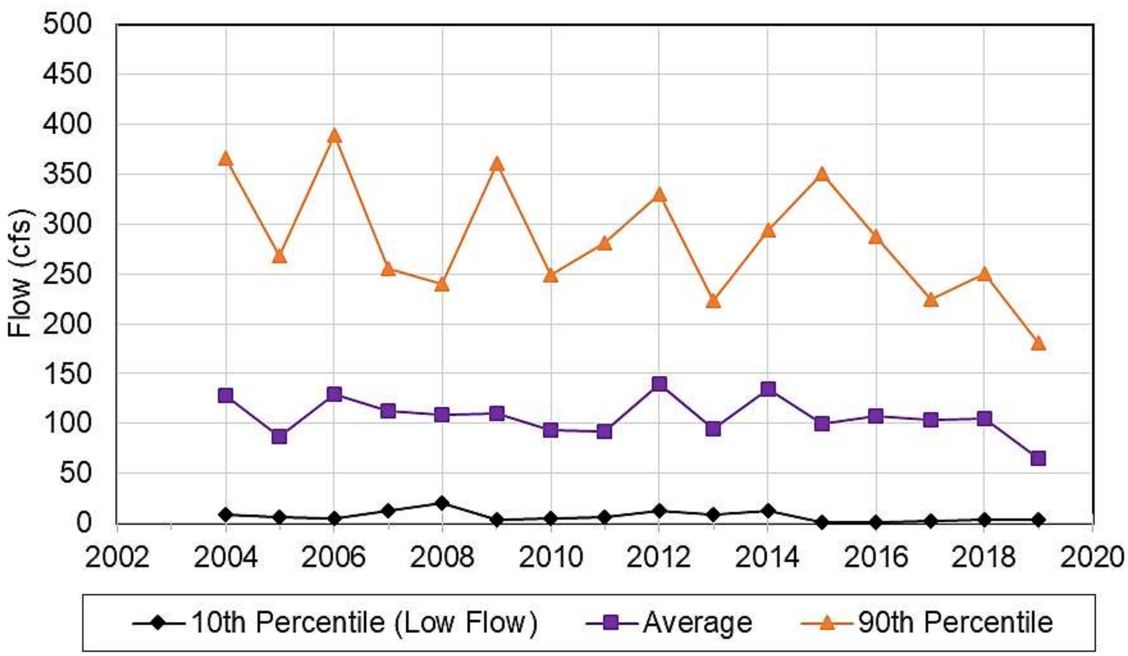

Figure 3-5. Average annual flows Whatcom Creek at Derby Pond

Source: City 2020e.

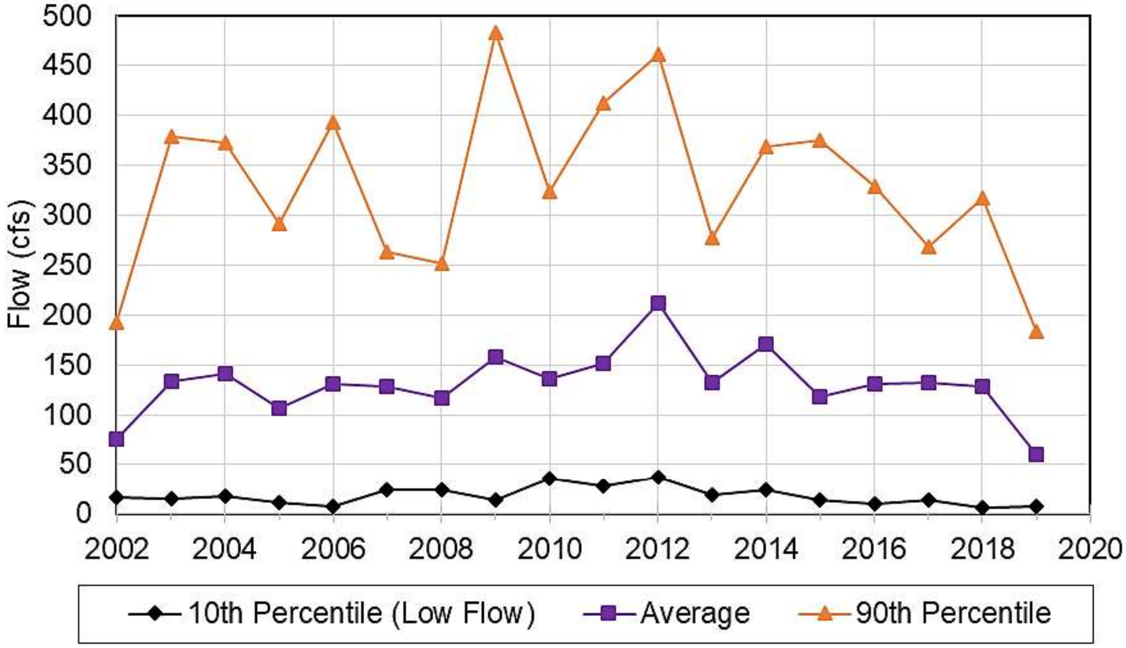

Figure 3-6. Average annual flows Whatcom Creek at Dupont

Source: City 2020f.

3.1.2 Pulse Data Analysis

A pulse count analysis of hydrologic data provides a useful metric to evaluate stream health. Stream health is affected by the frequency and duration of low and high flow events and a pulse count analysis uses existing flow data to count and measure the durations and frequencies of high and low flow events. A pulse refers to a large deviation, either lower or higher, from the long-term daily average flow. For this analysis, a low flow pulse was defined quantitatively as the occurrence of daily average flows that are equal to or less than a threshold set at 50 percent of the long-term daily average flow rate. A high flow pulse was defined as the occurrence of daily average flows that are equal to or greater than a threshold set at twice (two times) the long-term daily average flow rate. High flow pulses occur more frequently in urbanized settings as a result of shorter time of concentrations because of increased impervious area. The expected hydrologic response to urbanization is as follows:

- Baseflow is more frequently interrupted by storm flows, resulting in more frequent high pulse events
- Peak stream flow magnitudes are higher, but durations are shorter
- Flows deviate more frequently from the long-term daily average flow
- Pulse durations decrease as the runoff hydrograph increases in amplitude but decreases in period

Three metrics for the low and high pulse were calculated: count, duration, and range. The five streams have similar values for low and high pulse count and duration. The low and high pulse count values are closer to those of a fully forested condition than a fully urbanized condition.

The results suggest a low percentage of hardscape, a high percentage of vegetation that intercepts rainfall, and/or well-functioning stormwater infrastructure and BMPs. Having an impoundment upstream of a creek would dampen the peak and spread the duration, just as a BMP would, thereby reducing the number of high pulses for large events. Ideally, operating the dam in concert with expected rain events could improve stream health as it could further dampen the pulse, and reduce sediment loss due to channel bank erosion. However, looking at the data on an annual basis would limit the ability to evaluate dam operations.

The third metric, pulse range, is less intuitive and researchers developed this metric after the original count and duration metrics. The range is the number of days between the start of the first flow pulse and the end of the last flow pulse during a year. This provides an indication of whether pulses are seasonal or annual. The low and high pulse ranges increase with greater urbanization. The five streams have similar results. The low pulse range is likely mostly indicative of when baseflow occurs and suggests that runoff pulses can interrupt this pattern throughout this season. The high pulse range (HPR) is annual and indicates that high flows can occur at any time. However, the wide range means any given storm could generate a pulse and be more a function of the types of storms than the runoff response.

Research conducted in Puget Sound lowland streams shows substantial confidence that a goal of raising benthic index of biotic integrity (B-IBI), a measure of stream health, out of the lowest index tier (less than 16 indicating poor stream health) to a fair-condition tier (greater than 16) cannot be achieved if HPCs remain above 15 excursions and HPR is greater than 200 days (King County 2013). Bellingham urban streams as shown in the data in Table 3-1 have HPC below 15, and HPR greater than 200 days, indicating the possibility of similar conclusions. Of course the institution of distributed green stormwater infrastructure (GSI) practices and stormwater BMPs can help reduce the effect of urbanization, thereby bringing HPC up and HPR down.

A comparison to rainfall patterns and additional metrics, which were beyond the scope of the SSWCP update, may be needed to further interpret the meaning of the pulse metrics.

The pulse count data for the five monitoring sites are presented in Table 3-1.

Table 3-1. Hydraulic metrics from City of Bellingham monitoring locations for low and high pulse count and range

		Chuckanut Creek at Arroyo Park gage station			Whatcom Creek at Derby gage station			Whatcom Creek at Dupont gage station			Padden Creek at Fairhaven Park gage station			Squalicum Creek at West Street gage station		
Variable	**Description (units)**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**
Low pulse count	Number of low pulse events per year (count)	1	3	6	1	3	6	1	3	4	1	3	6	1	4	6
Low pulse duration	Mean duration of low pulse events (days)	27	70	208	29	71	218	35	82	250	26	77	206	8	70	180
Low pulse range	Range each calendar year over which low pulse events occur (days)	189	235	292	201	257	312	120	225	306	177	227	297	60	249	334
High pulse count	Number of high pulse events per year (count)	4	6	9	1	4	8	1	4	8	4	7	9	4	7	9
High pulse duration	Mean duration of high pulse events (days)	4	9	15	0	17	51	3	14	32	5	11	21	4	9	16
High pulse range	Range each water year over which high pulses occur (days)	268	341	364	0	298	364	2	309	364	280	36	364	196	338	364

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3.1.3 TQ Mean Analysis

"TQ mean" is the fraction of time that stream flow exceeds the daily mean stream flow during the year. This hydrologic measure of stream flashiness provides insight to stream response to urbanization. "Flashiness" is a term that describes how quickly stream flow rises and falls in response to storm events. Urbanized watersheds tend to be flashier than forested or undeveloped watersheds because the impervious areas in the built environment intercept precipitation and quickly direct the runoff to streams, whereas in a forested watershed the precipitation is absorbed into the ground or is returned to the atmosphere through evapotranspiration processes, thus resulting in lower stream flow. Stream flow in a forested watershed, relative to the mean annual flow, tends to have longer periods (sustained flow periods) with lower peak flow rates (smaller amplitudes).

TQ mean is the fraction of time during a water year that average daily flow is greater than average annual flow. Stream data with long periods when the average daily flow was above the mean annual flow produces a relatively high TQ mean value. Long periods of flow above the mean annual flow suggest that the watershed response to storm events mimics more natural conditions. Relatively small TQ mean values indicate short durations when the average daily flow is above the mean annual flow, indicating flashier streams, which is typical of urbanizing watersheds.

TQ mean trends for the years 2005 to 2019 are increasing at four of the five gaging stations (Chuckanut Creek is decreasing). The increasing trends suggest that stormwater management practices are having positive effects on flow quantities. TQ mean trends are shown in Figure 3-7 through Figure 3-11. It is difficult to develop conclusions on the effect that the operation of the control dam has on Whatcom Creek; however, a detailed study that would include tracking operation and stream response could show that dam control could also function similarly as a BMP by prolonging stream flow above average flow.

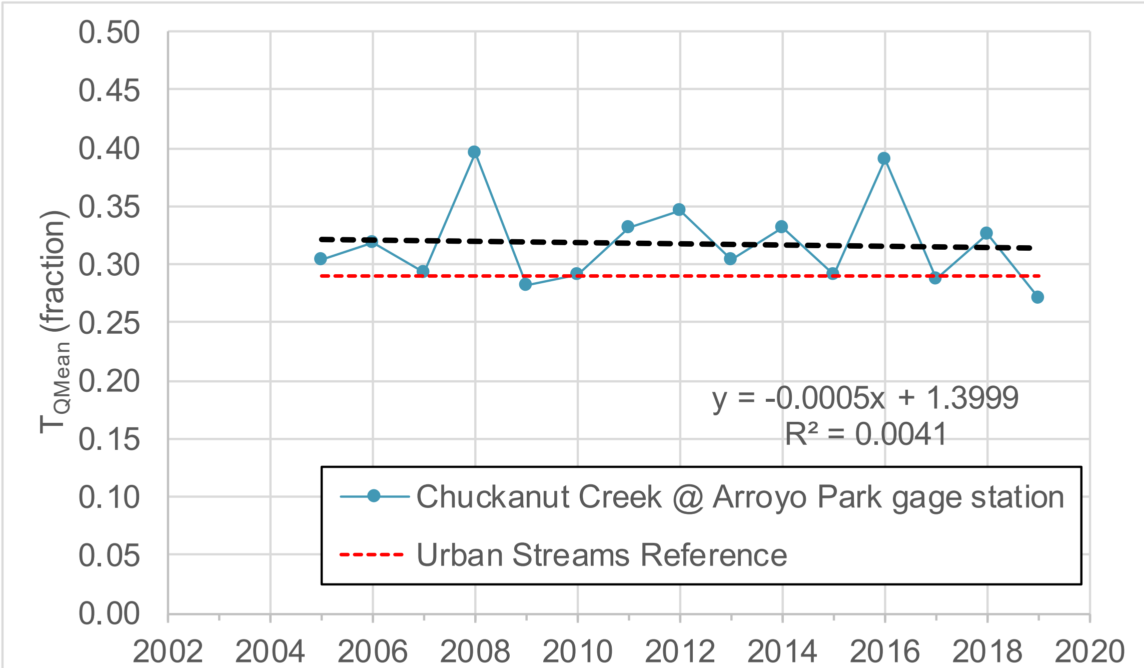

Figure 3-7. TQ mean Chuckanut Creek at Arroyo Park gage

Source: City 2020g.

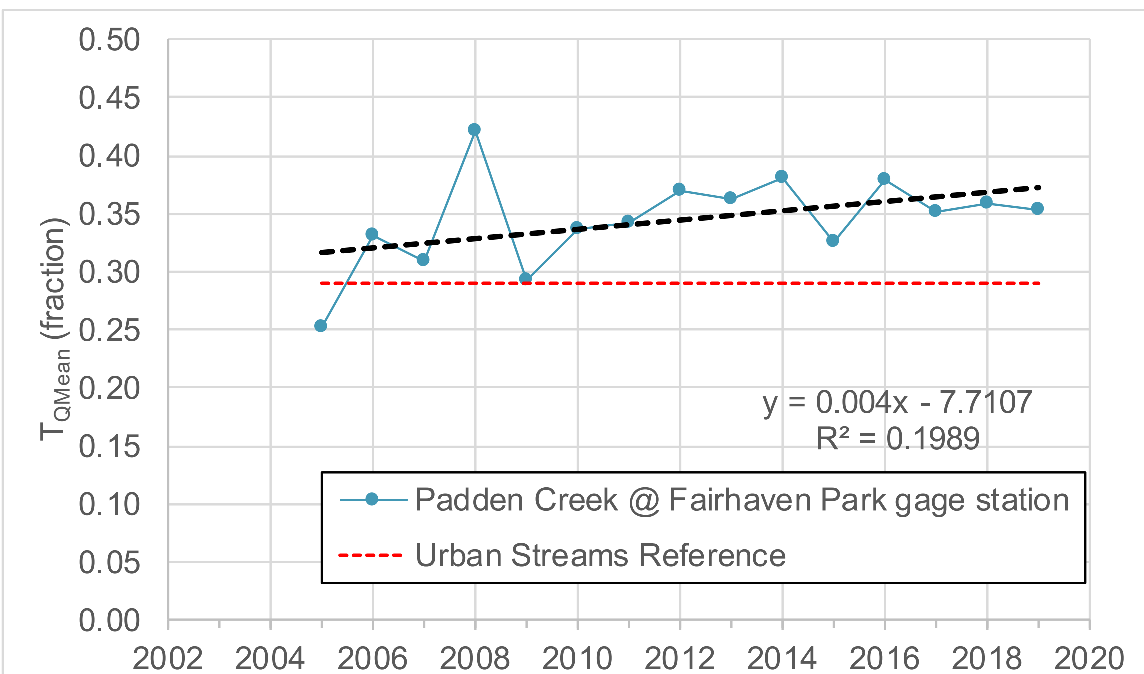

Figure 3-8. TQ mean Padden Creek at Fairhaven Park gage

Source: City 2020g.

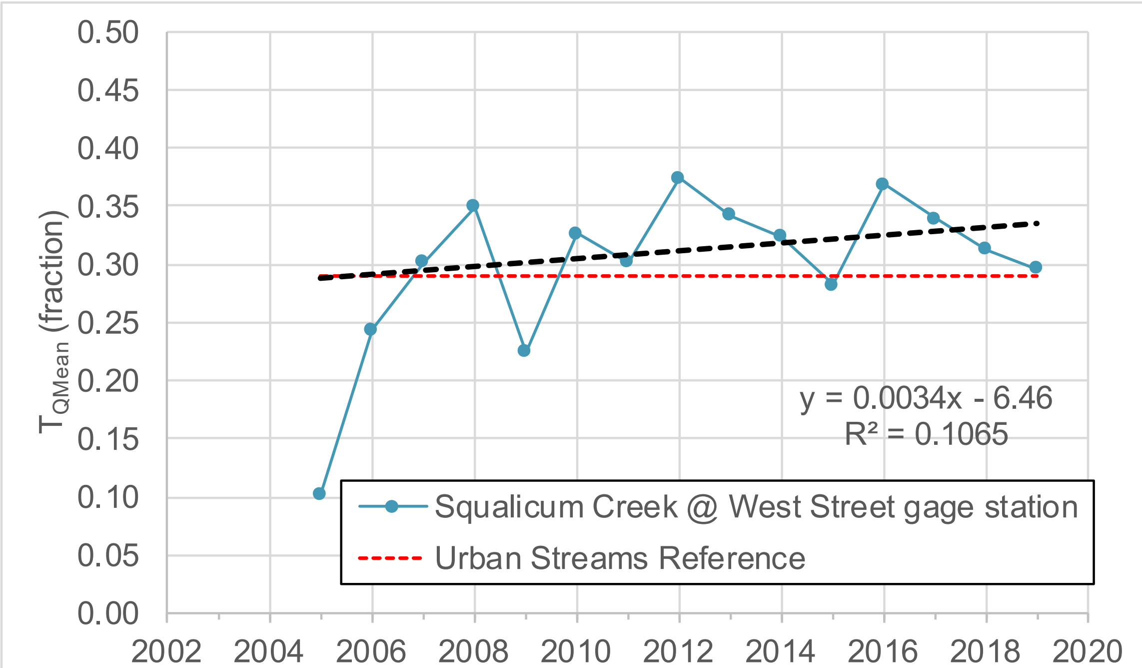

Figure 3-9. TQ mean Squalicum Creek at West Street gage

Source: City 2020g.

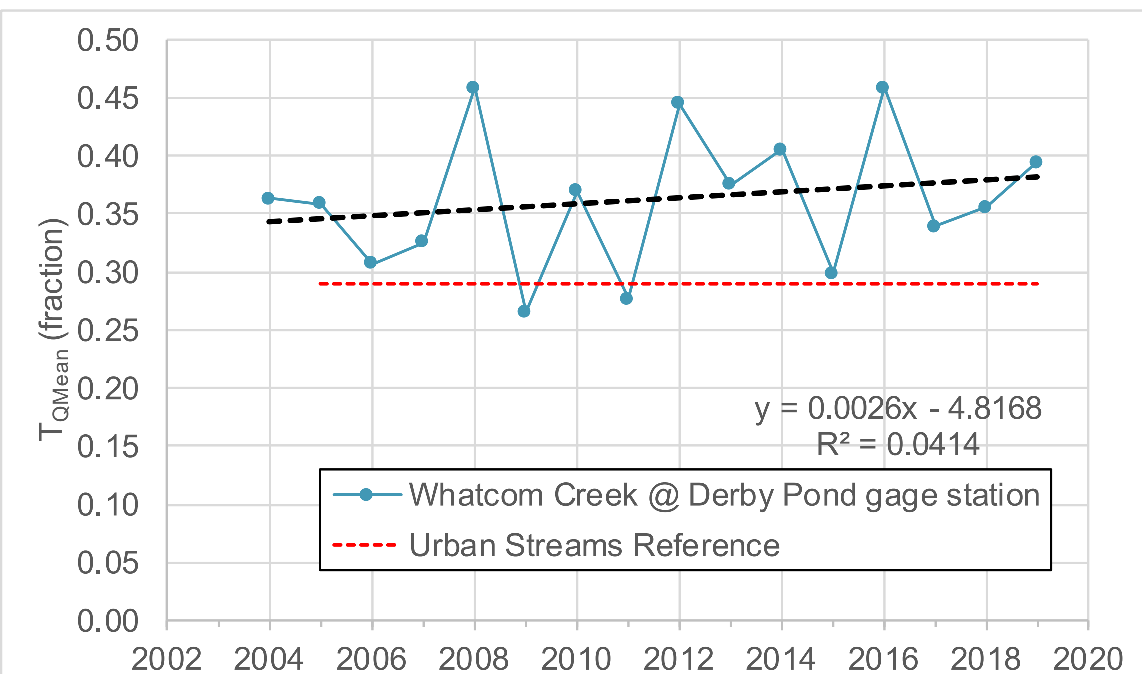

Figure 3-10. TQ mean Whatcom Creek Derby gage

Source: City 2020g.

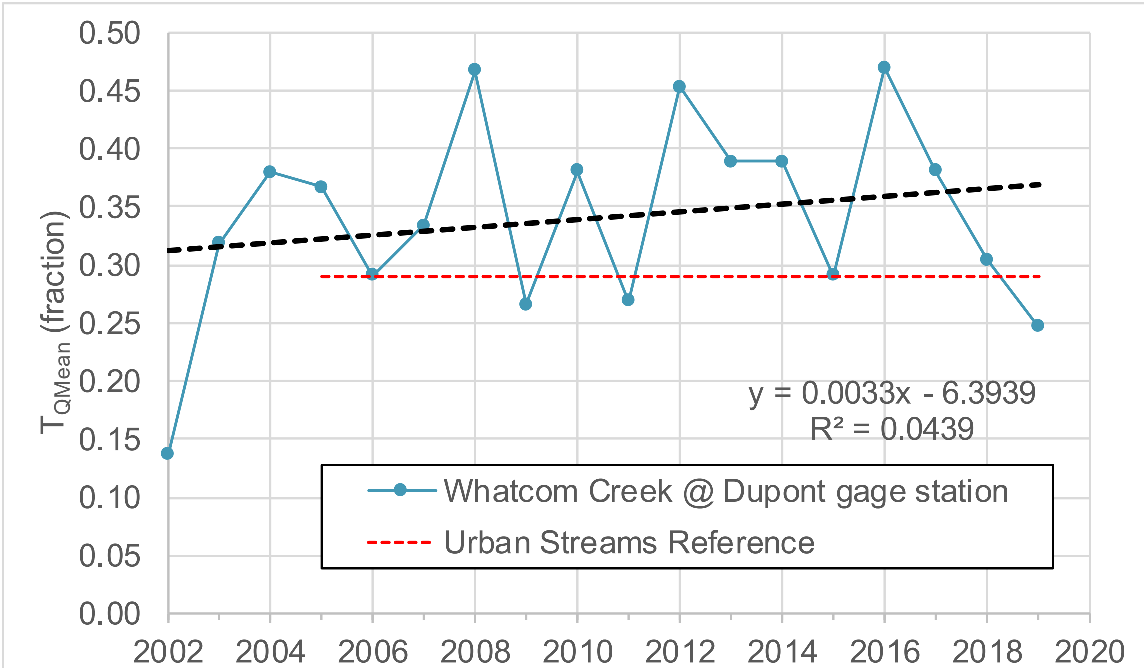

Figure 3-11. TQ mean Whatcom Creek Dupont gage

Source: City 2020g.

3.2 2007 City of Bellingham Comprehensive Plan Modeling

Under the 2007 City of Bellingham Stormwater Comprehensive Plan, continuous-flow duration hydrologic and hydraulic models were developed to identify stormwater conveyance system locations that were undersized and potentially at risk of failure. Sub-watersheds modeled included the following:

- Silver Creek
- Squalicum Creek
- Silver Beach Creek
- Whatcom Creek
- Padden Creek
- Chuckanut Creek

Each of the sub-watersheds was further subdivided into sub-basins, thus producing numerous hydrologic boundaries throughout the city. These sub-basins were used in the systems analysis and retrofit plan that are described in Chapter 7.

3.2.1 Model Outputs

The results of the model, showing the extent of potential capacity enhancements, are summarized in Table 3-2 below.

Table 3-2. Sub-basin storm conveyance upgrade quantities

Sub-basin	Improvement project group	Pipe upgrade quantity (lf)
Baker and Spring	Culverts, storm drains	3,650
Silver	Culverts, storm drains	1,300
Squalicum	Culverts, storm drains	2,000
Whatcom Creek	Ellis Street 1	2,250
	Ellis Street 2	2,050
	King/Virginia/Lincoln	3,400
	Meador Avenue	200
	State Street	900
	Misc. Whatcom outfalls	250
Fever Creek	Kentucky Street	1,050
	Orleans/Nevada	1,600
	Valencia/North/Verona	3,500
	Misc. improvements	700
Cemetery Creek	*Insufficient conveyance data	
Hannah Creek	Lakeway Drive	800
	Raymond Street	200
Lincoln Creek	Lincoln Creek	1,050
Total		**24,900**

3.2.2 Erosive Flow Analysis

Ecology bases its NPDES permit flow control standard (Minimum Requirement 7) on the range of erosive flows in western Washington streams. Based on work done at the University of Washington by Booth and Jackson (1997), it was found that the typical range of erosive flows in western Washington streams is from half of the 2-year peak flow to the full 50-year peak flow. This standard erosive flow range is the basis for Ecology's Minimum Requirement 7.

Local municipalities have the option of conducting watershed-specific erosive flow analysis to replace Ecology's standard erosive flow range. As part of the 2007 Stormwater Comprehensive Plan, this erosive flow analysis was done for Whatcom Creek. The analysis focused on determining the flow at which erosion/scour of the stream channel bedload begins. Controlling erosive flows will aid in reducing sediment transport from eroding streams, and enhance stream function and habitat preservation.

A summary of the results is presented in Table 3-3 below, indicating the estimated discharge corresponding to sediment movement and its critical shear stress, respectively.

Table 3-3. Whatcom Creek minimum erosive flows

Site	Estimated discharge at incipient point of sediment motion (cfs)		Critical shear stress (lb/ft²)
	Slope = 0.03 (ft/ft)	Slope = 0.01 (ft/ft)	
Falls Park Reach Site 1	29.5	101.1	0.83
Redtail Reach Site 1	2.4	8.2	0.45
Redtail Reach Site 2	3.9	13.3	0.60
Redtail Reach Site 3	3.6	12.4	0.52
Redtail Reach Site 4	6.3	21.5	0.88
Salmon Park Reach Site 1	4.1	14.2	0.59

A Wolman pebble count survey is a process to establish the range of sediment size in a stream. The pebble count analysis shows that erosive flows in Whatcom Creek generally start in the flow range of 10 to 30 cubic feet per second (cfs). The general assumption, from various geomorphic studies, is that these flows should roughly correspond to bankfull flow, which generally corresponds to a flow rate with a return frequency of slightly less than the 2-year return frequency flow.

Parametrix conducted an erosive flow analysis of Whatcom Creek tributaries (Hannah, Lincoln, Fever, and Cemetery) in March 2006. The erosive flow results from the 2007 Stormwater Comprehensive Plan are shown in Table 3-4, indicating estimated discharges at the time of sediment movement for two different slopes along with the critical shear stress (both low and high). D50 is the median particle diameter of the 50th percentile sediment particle, while D84 is the median particle diameter of the 84th percentile sediment particle.

Table 3-4. Whatcom Creek tributaries minimum erosive flow (Bathurst Equation)

Site	Stream width (ft)	Slope = 0.01 (ft/ft) Low D84	Slope = 0.02 (ft/ft) High D84	Low D50 (lb/ft²)	High D50 (lb/ft²)
Site 1: Hannah Creek	10	6.8	24.9	0.10	0.15
Site 2: Hannah Creek	10	6.8	24.9	0.10	0.15
Site 3: Lincoln Creek	6	1.4	5.3	0.05	0.07
Site 4: Fever Creek	12	4.9	17.8	0.07	0.10
Site 5: Cemetery Creek	15	48.3	182.3	0.30	0.42

There is a large range of minimum erosive flows for each tributary stream. No attempt was made to try to correlate these flow values to Ecology's 50 percent of the 2-year flow at these sites.

Minimum Requirement 7, Flow Control, requires property developers to provide measures to reduce runoff from their sites to the forested pre-developed condition. The intent of this requirement is to prevent increases in the frequency of flooding due to new development.

Detention facilities are often designed to maintain peak flow rates at their pre-development levels (e.g., forested conditions) for certain recurrence intervals (e.g., 2- and 10-year). Facilities that control only peak flow rates, however, usually allow the duration of high flows to increase, which may cause increased erosion of the downstream system. For example, a detention facility may keep the magnitude of a 2-year flow from increasing, but the amount of time that flow rate occurs may double. Therefore, Ecology bases the flow control standard on outgoing flow rates that provide protection from erosion, as such detention systems also have a duration control standard for geomorphically significant flows (flows capable of moving sediment). Such detention systems employ lower release rates and are therefore larger in volume, resulting in increased facility size, and in turn higher implementation cost.

Ecology offers a basin-specific method for determining flow control facility sizing. The Ecology-approved watershed approach for establishing flow control standards is based on the unique characteristics of a target watershed that takes into account the specific sediment size and flow rates of the watershed. It requires a detailed study to establish flow rates at various locations in the watershed and a detailed analysis of the dominant sediment regime. The 2007 erosive flow analysis is an example of such a detailed study. The values in Table 3-4 could be used to establish threshold discharge rates in the respective watersheds. Further analyses to establish differences in runoff rates from a fully developed watershed to the values calculated in 2007 could be the basis of alternative flow control standards. Any proposal to use the alternative method would require approval by Ecology.

In conclusion, this alternative approach is not recommended at this time because the generic approach does not appear to be a barrier to redevelopment. If the City experiences problems using the generic approach, for example costs for stormwater mitigation are explicitly identified by developers, then the City could consider developing the watershed-specific standard. It is possible that the findings would result in smaller facilities, thus incentivizing developers to rebuild.

3.2.3 2020 Model Evaluation

The stormwater modeling software provided to the City in 2007 gave City staff a range of tools to use for present and future watershed planning. The intent of the model was also for City staff to evaluate proposed land use developments and mitigation measures within the city's watersheds, determine the effectiveness of upgrading the City's stormwater conveyance system, and simulate how changes in the City's urban growth area will impact stormwater flows in the city's streams. The modeling software options include the ability to update the model with new land use data as they become available.

The modeling and under-capacity pipe analysis has been used during development review by the City in a limited manner to evaluate the potential for the system to handle additional development. It is understood that the previous modeling effort was limited in scope and budget to allow further assessments.

As part of the 2020 SSWCP update, the 2007 hydrologic and hydraulic models were evaluated for the possibility of updating them to current land use conditions and possible use for basin planning. The objective of this task was to provide an assessment of the City's existing hydrologic and hydraulic models and determine their potential for use in completing the modeling and analyses needed to support the conveyance modeling conducted in the 2020 SSWCP, specifically for analysis of Lower Padden Creek, Lower Squalicum Creek, Lower Baker Creek, Lower Spring Creek, and Baker Creek Tributary. The City provided model input and output files, available documentation, and supporting data to the HDR Engineering, Inc. (HDR) team for this evaluation.

Appendix A contains the technical memorandum that details the results of the model assessment. The assessment has the following conclusions:

- WWHM models of 2007 conditions for the Chuckanut Creek, Padden Creek (Lower and Upper), Silver Creek, and Silver Beach Creek basins are available.
- Updates to the models of the four basins listed above to simulate full buildout conditions would be relatively straightforward.
- WWHM models of the Whatcom Creek and/or Squalicum Creek basins would be more difficult and would rely on being able to locate the actual WWHM models for those basins or all of the necessary input data.
- Data gaps in the existing models need to be closed before the models can be used for their stated objectives. The analysis provided a scope and budget to update the models and close the data gaps. The technical memorandum that describes the analysis and includes the scope for updating the models is included in Appendix A.
- The process for opening the model files in Western Washington Hydrology Model 3 (WWHM3) as described in the 2007 report was not successful. It is recommended to set up new WWHM models from scratch for future use.
- The archived Storm Water Management Model (SWMM) model was missing SWMM input files that could be directly used in current versions of SWMM. Furthermore the 2007 Stormwater Comprehensive Plan provides limited detail on how the data for the SWMM models were derived. Some of the data apparently came from the City's GIS and other data were obtained from an earlier 1995 Watershed Master Plan study.
- The 2007 report also states that "Missing or incomplete GIS conveyance system data were filled based on 'adjacent data.'" It is recommended to collect measured-down distances between the rim and the inverts in catch basin structures with missing data.
- Given the lack of usable SWMM input files, the lack of clear documentation on how the SWMM input data were derived, and the statement that the 2007 models were only "conceptual and intended for planning-level decision-making," it is recommended that creating new SWMM models for the five targeted sub-watersheds would be more efficient and cost-effective than spending any additional effort to locate or use the earlier SWMM models.