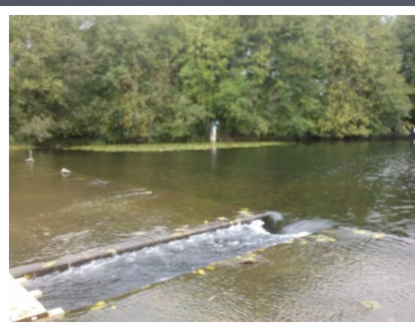
Willowmoor Restoration Design Hydrology

Phase 1 – Hydrologic Characterization



October 2013

King County

Willowmoor Restoration Design Hydrology
Phase 1 – Hydrologic Characterization

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Executive Summary

King County (County) is planning the Willowmoor Project, a flood control and habitat restoration project for the Sammamish River Transition Zone (TZ), which extends from the Lake Sammamish outlet weir approximately 1,400 feet downstream through Marymoor Park. Northwest Hydraulic Consultants (NHC) was contracted by the County to provide recommendations for design hydrology for the Willowmoor project. The initial phase of this work focuses on characterizing the original U.S. Army Corps of Engineers (Corps) design hydrology within the current hydrologic context and on identifying potential future hydrologic conditions to provide background for a robust project design.

The Sammamish River Flood Control Project was completed by the Corps in 1964 to provide spring flood control for the Sammamish River valley. The project was designed to accommodate an event similar to the March 1950 storm, which was the spring flow of record at the time. The design objectives were to eliminate flooding for a design flow of 1,500 cfs in the Sammamish River downstream of Bear Creek while keeping Lake Sammamish levels below 29.0 feet NGVD (32.6 feet NAVD).[1] The design flow was characterized by the Corps as a 10-year annual flood or a 40-year spring flood, meaning that on average that flow had a ten percent chance of occurring at all or a 2.5 percent chance of occurring after March 1 in any given year. This frequency estimate is relatively consistent with results of current frequency analysis on 18 years of peak flow data (1940-1957) from the discontinued Sammamish River near Redmond gage that would have been available to the Corps during project design.

The original Lake Sammamish outlet weir was modified in 1998 to enhance summer flows to improve fish passage into Lake Sammamish. Modifications included adding a low flow notch and flattening the weir profile on either side of the notch. The change to the weir profile resulted in raising the crest elevation by up to half a foot.

Water levels in Lake Sammamish, and corresponding discharges, have been shown to be affected by conditions through the TZ and downstream to Bear Creek. Vegetation management practices in the TZ downstream of the weir have varied over time, and impacts of different vegetation conditions on flow capacity in the TZ have been demonstrated in several previous studies and by shifts in the stage-discharge relationship at the weir corresponding to changes in vegetation management. A reduction in lake outflows associated with high Bear Creek discharges—the Bear Creek backwater effect—has been demonstrated with measurements showing variable discharge at the weir for the same lake level during large events and can be reproduced by a hydraulic model of the system.

Existing hydrologic and hydraulic models of the Lake Sammamish/Sammamish River system have been used to characterize existing conditions—e.g., to determine flood inundation extents for FEMA mapping—and to explore the sensitivity or impact to the system of observed and proposed changes in the TZ, such as vegetation and sediment levels. The hydraulic model is well-calibrated to water levels at the weir and downstream of the TZ and reproduces lake levels quite well. The hydrologic models, which have been used to estimate long periods of inflows for the hydraulic model, are less accurate in reproducing observed flows on Bear Creek and Issaquah Creek.

Based on nearly 50 years of observed peak flows since construction of the weir, the 10-year flow in the Sammamish River downstream of Bear Creek is currently about 2,000 cfs, which is 33 percent higher than the 10-year flow characterized by the Corps during project design. It seems likely that this increase

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[1] Lake Sammamish water levels have been customarily expressed relative to the NGVD29 (or MSL) datum. The conversion factor to the NAVD88 vertical datum is +3.59 feet. This report will clearly indicate the datum for any elevations and provide elevations on both scales where reasonable.

is primarily a result of the original project, which increased the capacity of the lake outlet and downstream channel. Development in parts of the basin, especially Bear Creek and east Lake Sammamish, has likely contributed to increased peak flows, but would not be expected to have so substantial an impact in a system with significant storage, as is provided by Lake Sammamish. Examination of precipitation and streamflow trends indicates that climate is also not a driving factor; there is no long-term evidence of increasing precipitation or streamflow trends.

Analysis of lake levels, however, shows a significant increase in the amount of time that Lake Sammamish exceeds the Corps-defined ordinary high water (OHW) level of 27 feet NGVD (30.6 feet NAVD). This is consistent with anecdotal reports from lakeside homeowners. Both visual inspection and statistical tests suggest that higher lake levels begin around 1998, and these changes would be consistent with weir modifications that reduce lake outflow at low to moderate lake levels. The data do not link the weir modifications as clearly to maximum lake levels (above about 28 feet NGVD).

In looking at the historic events with the highest observed lake levels, we can identify a number of contributing factors. Inflow is certainly a primary driver but cannot explain the lack of strong correspondence between the events with the highest peaks or inflow volumes and those with the highest lake levels. Examination of the record indicates that lake level prior to the event (i.e., the starting condition) and coincident high flows on Bear Creek are also recurring factors in several extreme lake level events. Different lake level response to events where inflow, starting level, and Bear Creek flows are similar also suggests that vegetation conditions in the TZ have an influence on high lake levels. It is interesting to note that nearly 90 percent of the events where the lake has exceeded 29 feet NGVD (32.6 feet NAVD) since 1964 have occurred since 1989, when annual TZ maintenance was discontinued. In contrast, only half of the highest Issaquah Creek flows in the same period have been since 1989. (Issaquah Creek is the largest tributary to Lake Sammamish and the only one with a streamflow record extending back to completion of the Sammamish River project.)

The review and analyses documented in this report provide a characterization of the current hydrologic setting and the various factors and influences that have affected performance of the weir and TZ over the past couple of decades. Hydrologic design conditions for the Willowmoor project will need to take into account these various influences on flow and lake level. For this reason, and because the project is expected to have a broader range of objectives, it is unlikely that a single design flow and lake elevation can continue to be used. The design process will also need to take some account of potential future hydrologic conditions to ensure that the selected project will continue to meet performance objectives going forward.

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1 Introduction

King County (County) is planning the Willowmoor Floodplain Restoration Project (Willowmoor Project), a flood control and habitat restoration project for the Sammamish River Transition Zone (TZ). The TZ extends from the Lake Sammamish outlet weir approximately 1,400 feet downstream through Marymoor Park.

Northwest Hydraulic Consultants (NHC) was contracted by the County to provide recommendations for design hydrology for the Willowmoor project. The initial phase of this work focuses on characterizing the original U.S. Army Corps of Engineers (Corps) design hydrology within the current hydrologic context and on identifying potential future hydrologic conditions to provide background for a robust project design. The goals of this effort are to evaluate the relevance of the original Corps design hydrology with respect to current and future conditions, to determine whether updated hydrologic design criteria are warranted, and, if so, to recommend next steps for developing updated hydrologic design criteria.

As part of the Phase 1 effort, NHC reviewed the Corps design documentation and subsequent available studies of Lake Sammamish and the Sammamish River; assessed existing hydrologic and hydraulic modeling; and statistically evaluated precipitation, flow, and lake level records. This report documents these reviews and analyses and provides recommendations for an approach to determine an appropriate suite of design flows and hydrologic conditions for the Willowmoor project.

2 Review of Previous Studies

NHC reviewed several previous studies and reports related to the Sammamish River TZ and Lake Sammamish (Table 1). The review was limited to readily available documents, though information from additional studies is incorporated by reference as relevant. We believe that this review provides a reasonably good characterization of the original design context and of subsequent changes that may affect hydrologic planning and design for the Willowmoor project. The following sections summarize key relevant findings from previous work.

Table 1. List of documents reviewed

Abbreviated Title	Date	Author
General Design Memorandum	1962	Corps of Engineers
Operation and Maintenance Manual, Vol 1	1964	Corps of Engineers
Lake Sammamish Special Study	1997	Corps of Engineers
Results of Re-Calibration of Sammamish River	2002	Corps of Engineers (draft memo)
Habitat Enhancement Conceptual Proposal	2003	King County
Lake Sammamish Ordinary High Water Mark Study	2004	Watershed Company (for City of Bellevue)
Transition Zone H&H Investigation	2004	WEST Consultants (for King County)
Sammamish River Floodplain Mapping Study	2010	NHC (for King County)
Climate Change Impacts on River Flooding	2010	King County
Findings on Lake Sammamish Outflow	2012(a)	King County
Transition Zone Sediment Removal Feasibility Study	2012(b)	King County

2.1 Project History

The Sammamish River Flood Control Project was completed by the Corps in 1964 to provide flood control for the Sammamish River valley. The project consisted of lowering , enlarging, and in some places straightening the main river channel; construction of the TZ connecting the modified channel with the Lake Sammamish low water control; and regrading of the downstream ends of major tributaries to meet the lowered Sammamish River channel, as well as an overflow channel on Bear Creek (USACE, 1962). At the time of construction, land use along the river was largely agricultural, and the primary goal of the project was to "substantially [prevent] all spring flood damage" (USACE, 1962, p. 7) without Lake Sammamish levels exceeding 29.0 feet NGVD[2] (32.6 feet NAVD).

The March 1950 flood, which was the maximum spring (after March 1) flood of record at the time, was selected as the inflow design flood. The Corps determined that the March 1950 flood had an annual recurrence interval of ten years and a spring recurrence interval of 40 years (USACE, 1962). The design memorandum does not specify the data used in this frequency analysis. Based on the available streamflow data reported in the design memorandum, it is likely that the frequency determination was based on the Sammamish River flow below Bear Creek[3].

The design criteria for the TZ were to "pass the design flood of about 1,500 [cfs] (including Redmond Bear Creek discharge) without exceeding a lake elevation of 29.0 feet [NGVD] while maintaining present minimum lake elevations (USACE, 1962, p. 7)." It is interesting to note that the 1,500 cfs design flow is higher than the March 1950 flow (1,360 cfs per the design memorandum) and close to the maximum flow of record at the time for the Sammamish River near Redmond gaging station[4] (1,520 cfs in February 1951). Per the design memo, the 1,500 cfs design flow applied to the TZ (upstream of Bear Creek) and to the main channel from the end of the TZ all the way downstream to Little Bear Creek near Woodinville. Thus, TZ design capacity was relatively high compared to the channel below Bear Creek.

The design memorandum does not specify separate design flows for the TZ above Bear Creek and the coincident Bear Creek contribution, though the design flow in the TZ (i.e., outflow from the lake) has subsequently been interpreted by the Corps to be 1,200 cfs (e.g. USACE, 2002). The basis for this interpretation is not entirely clear from the review conducted for this study. The Conceptual Proposal for the TZ (King County, 2003) reports 1,200 cfs as the 10-year annual recurrence flow at the TZ, and the 2007 Flood Insurance Study (FIS) used 1,233 cfs as the 10-year flow at the weir (as reported in King County, 2012a). The source of the FIS flow is not documented in the available reports. Since we are unaware of systematic data collection in the reach above Bear Creek until King County installed gage 51m in 2001, it seems likely that these values may have been based on 10-year lake levels and outlet rating curves. An internal Corps memo (USACE, 2002) suggests that there had been an assumption of a one to one correspondence between stage and discharge frequencies for the lake.

Support for a corresponding 300 cfs contribution from Bear Creek is also unclear. The Corps memo suggests that a defined ratio of Bear Creek to Sammamish River flows may have been assumed, though a 20 percent design ratio (300 cfs from Bear Creek out of 1,500 cfs on the Sammamish River below Bear

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[3] Today's Bear Creek is referred to in the design memorandum as Redmond Bear Creek; Little Bear Creek is referred to as Woodinville Bear Creek.

[4] Sammamish River near Redmond (USGS 12125000) discontinued in 1957. Comparable to Sammamish River near Woodinville (USGS 12125200) activated in 1965. The Woodinville station drains about 5% more area (159 to 150 square miles).

Creek) would seem to be low given that the Bear Creek basin makes up roughly one third of the Sammamish River basin at the USGS gage site. The Corps memo reports an average contribution of 30 percent from Bear Creek (plus local inflow, assumed to be minor) to Sammamish River at Redmond flows over an unspecified monitoring period (possibly the overlapping period between discontinued Bear Creek and Sammamish River at Redmond USGS stream gages). The memo suggests that the difference could be explained by restrictions at the outlet reducing lake contributions to the flow, or that the design ratio was incorrect.

It seems clear that the 300 cfs flow is not intended to represent a coincident peak flow on Bear Creek. The Bear Creek peak flow for the March 1950 design event was 654 cfs and the 10-year annual recurrence flow based on the short Bear Creek record available at that time (1946 to 1958 at USGS 12124500) is 630 cfs. Review of the observed record shows that Bear Creek peak flows typically lead Sammamish River peaks, though lag time is variable and has been relatively small in several larger events.

As the local sponsor for the Corps' Sammamish River Project, King County assumed responsibility for operation and maintenance of the project. Per the Operation and Maintenance Manual (USACE, 1964) adopted by the County in 1965 (King County Commissioners, 1965), maintenance responsibilities included:

> Debris which may impede the flow in the channel shall be removed. The growth of trees and brush along the channel banks and levee face shall be prevented, as it can result in the displacement of bank stabilization, impede inspection and access to the channel banks and levee face, and impair hydraulic capacity of the channel. Particular attention shall be paid to the intake transition. The transition shall be repaired immediately if found deficient, as the characteristics of the transition are critical to flow. (USACE, 1964, p. 8)

Accepted stream and vegetation management practices have changed from these original operation and maintenance standards, and King County and the Corps of Engineers have worked jointly to develop subsequent agreements for maintenance policies consistent with project objectives, changing environmental regulations, and current policy (King County, 2012a). Impacts of different vegetation conditions on flow capacity in the TZ have been demonstrated in several modeling studies (USACE, 1997; NHC, 2010; King County, 2012a and 2012b) and through examination of rating curve shifts at the weir over the past decade (King County, David Funke, pers. comm., May 2013).

Information about vegetation management actions in the TZ was provided by King County (Nancy Faegenburg, pers. comm., June 2013). From project completion through 1989, annual maintenance, including mowing of both banks and sediment removal in the channel, was performed annually. In 1993, the County and the Corps reached an updated maintenance agreement calling for a 10-foot willow buffer along both sides of the low flow channel in the TZ and an alternating two-year mowing cycle for the high flow channel that would result in cutting of each bank every four years, with both banks cut the first year. Vegetation removal was suspended from 1994 through 1998. Cutting resumed in 1998 with a "one-time only maintenance regime establishing a 20' no-cut buffer zone on either side of the low flow channel; cutting one third of all woody stems between the buffer and the banks on both sides of the Transition Section; and removal of all non-native vegetation" (King County, Nancy Faegenburg, pers. comm., June 2013). In 2003, a mediation process between the County and the Corps restored the maintenance program from the 1993 agreement. Maintenance actions from 1998 through 2011, as provided by the County, are summarized in Table 2; no sediment management was reported during this period.

Table 2. TZ maintenance actions from 1998 to present

Year	Action	Right Bank	Left Bank
1998	Cutting to 20-foot buffer (fall)		X
1999	Cutting to 20-foot buffer (spring)	X	
2001	Selective thinning of willows on left bank; hand clearing on right bank	X	X
2003	Cutting to 10-foot buffer	X	
2004	Cutting to 10-foot buffer		X
2008	Mechanical cutting	X	
2009	Hand cutting		X
2010	Mechanical cutting		X
2011	Intensive mowing	X	X

The Corps modified the Lake Sammamish outlet weir in 1998 to enhance summer flows to improve fish passage into Lake Sammamish (King County, 2012b). The original wood sill with a shallow v-section was replaced with a flat-crested concrete weir with a low-flow notch in the center. The notch lowered the minimum discharge elevation by 0.65 feet, and the crest was raised by as much as half a foot per the Corps' design drawings (included in King County, 2012b) to ensure sufficient flow through the notch (Merri Martz, pers. comm., October 2013). This also served to raise summer lake levels by roughly the same amount (Merri Martz, pers. comm., October 2013).

2.2 Hydrologic Data Analysis

Several studies have used gage data analysis, modeling, or both to evaluate hydrologic and hydraulic conditions for Lake Sammamish and through the TZ. This information is helpful in assessing how hydrologic and/or hydraulic conditions may have changed since project construction.

2.2.1 Lake Levels

The Corps conducted a Special Study of Lake Sammamish in 1996 (USACE, 1997) that reviewed stage frequency for the lake and investigated impacts of four vegetation scenarios for the TZ on lake levels using HEC-1 and HEC-2 models.[5] It is notable that the 10-year lake elevation determined in the analysis exceeded the 29.0 feet NGVD (32.6 feet NAVD) flood control elevation (see Section 2.1) for all four of the vegetation management scenarios evaluated, including the "Initial Condition" scenario representing the design maintenance condition, which had a 10-year lake elevation of 29.6 feet NGVD (33.2 feet NAVD) (USACE, 1997).

In a later internal memorandum documenting recalibration of an earlier Sammamish River hydraulic model (USACE, 2002), the Corps concluded that "the Lake is expected to exceed the design elevation of 29.0 feet [NGVD (32.6 feet NAVD)] at the design discharge of 1,200 cfs" (USACE, 2002, p. 1). Failure to meet the design objective was attributed primarily to dense vegetation in the TZ, particularly the high flow bench, downstream of the weir. A comparison of the Corps' recalibrated model to previous model

[5] The HEC-1 model was used to compute lake stages for two historic events (1933 and 1951) that occurred prior to construction of the outlet control weir.

results indicated that the weir modifications, refinements to channel geometry, and channel constriction due to willow encroachment added about 0.4 feet to the simulated lake level.

The City of Bellevue conducted an ordinary high water (OHW) level study for Lake Sammamish in 2004 (Watershed Company, 2004). The study used several approaches to estimate OHW elevation, including field identification and statistical analysis of lake level data. The OHW level as determined from the mean elevation of field indicators of OHW level (e.g., change in vegetation type, debris lines, staining) surveyed for the study was 27.74 feet NGVD (31.32 feet NAVD)[6]. The study did not find statistically significant differences in OHW marks along different segments of the City of Bellevue shoreline, indicating that lake level is fairly consistent along most of the lake's western shoreline. Depending on the method used (e.g., mean annual peak, mode annual peak, 1.05-year recurrence interval elevation), the OHW level determined from historical record analysis (for the period from 1965 through 2003) varies between 27.42 feet NGVD (31.01 feet NAVD) and 28.28 feet NGVD (31.86 feet NAVD). The OHW study reports that the Corps-determined OHW level is 27.00 feet NGVD (30.59 feet NAVD) and that King County uses that same level as a basis for development setbacks. Increases in the OHW level are one of the primary concerns of Lake Sammamish property owners and shoreline groups, based on public input received in relation to King County's proposed sediment removal project (King County, 2012b).

Previous studies have noted that lake levels and flows in the TZ can be significantly impacted by vegetation in the channel and overbanks (expressed in the models as channel roughness) and, during large events, by backwater from high flows on Bear Creek. King County (2012a) explored two hydraulic influences on weir outflow and the rating curve used to determine flows at the weir (King County gage 51m).

The backwater impact from Bear Creek is evident for several historic high flow/high lake level events as a pronounced loop (referred to as a hysteresis) in the stage-discharge relationship at the weir. For two events (December 2010 and January 2006) for which flow *measurements* were taken at the weir throughout the event, discharge at the weir is initially lower at a given lake level, coinciding with the peak flow from Bear Creek, then increases as Bear Creek flows recede. This relationship is also evident for the December 1996/January 1997 event, with lake outflows estimated from an empirical function of Bear Creek and Sammamish River near Woodinville flows (see also Section 3.2). The unsteady HEC-RAS model developed for the floodplain mapping study (NHC, 2010) also demonstrates this backwater effect. Using a steady-flow sensitivity analysis approach, the County demonstrated that lake levels could increase by as much as 1.4 feet at roughly a 10-year discharge from the lake depending on the Bear Creek discharge; at lower weir discharges, Bear Creek inflows did not have an effect (King County, 2012a). This effect is discussed further in Section 3.2.

King County's Hydrologic Data Collection staff has employed four primary rating curves since 2001 (Figure 1). There was a significant upward shift (i.e., higher lake level for the same discharge) between 2006 and 2009, coinciding with a period with no TZ maintenance, followed by a significant downward shift following intensive mowing in 2011 (King County, David Funke, pers. comm., May 2013). Vegetation conditions do not explain the upward shift between 2003 and 2004, as cutting of both banks occurred over that period.

Hydraulic modeling conducted by the County found that channel roughness in the TZ could affect lake levels by as much as half a foot, though impacts decrease somewhat for larger events (King County,

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[6] Primary elevations for this study were reported in NAVD88. The conversion factor reported in the study is 3.59 feet, but converted elevations as reported fluctuate between 3.58 and 3.59 (possibly due to rounding). Elevations on both datums are reported here as in the document.

2012a). Modeling of estimated sediment accumulation in the TZ (King County, 2012a and 2012b) shows impacts on lake level ranging from 0.05 feet to about 0.3 feet, with the largest impacts at moderate flows (750 to 1000 cfs).

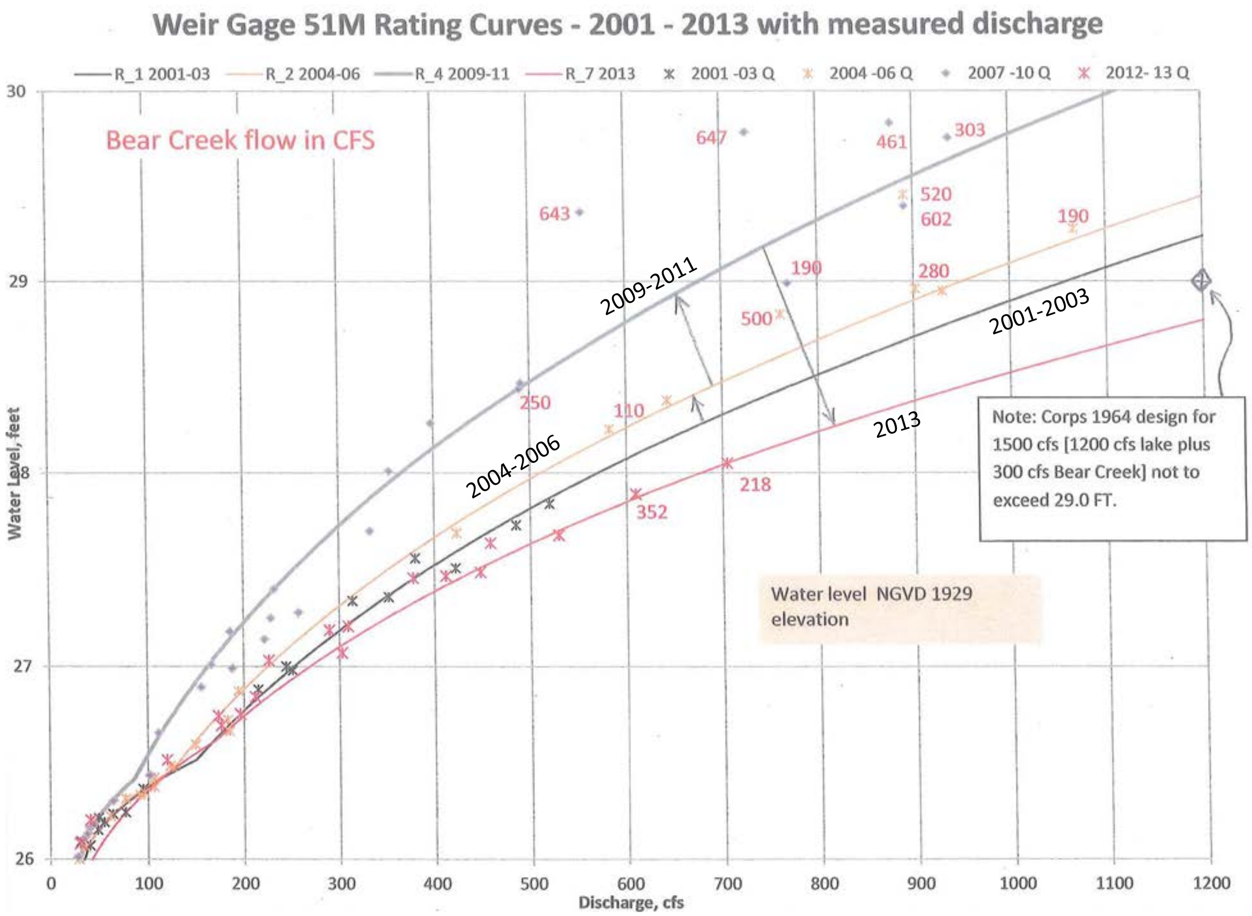


Figure 1. King County gage 51m rating curves and flow measurements for 2001 through 2013 (provided by King County)

2.2.2 Hydrologic Trends

King County conducted a thorough analysis of observed hydrologic data relating to Lake Sammamish outflows to the Sammamish River in 2010 and 2011 (King County, 2012a). The study included statistical analysis for trends in precipitation, lake levels, and Issaquah and Bear Creek flows, in addition to the evaluation of rating curves at the weir and sensitivity analysis for lake elevation and outflows to multiple vegetation and sediment management alternatives discussed in the previous section.

Precipitation analysis in this study consisted of trend analysis of monthly 1-day, 3-day, and 7-day maxima and monthly totals from the SeaTac daily record for 1949 through 2011. The only significant trend noted was a decrease in February totals for all four categories. There was also a moderate upward trend (though not statistically significant) in monthly and 3-day maximum precipitation for May, though small enough that changes were noted as not likely to be measurable (King County, 2012a).

The only highly significant statistical trend in Issaquah Creek flows (which make up roughly half of the Lake Sammamish inflow) was a decrease in September flows, which was noted as consistent with trends determined for other King County rivers (King County, 2010). The 2012 report notes that Issaquah Creek trends may not be representative of the remaining drainages into the lake, which are smaller and have experienced more significant development (on a watershed-scale basis). However, data are very limited for these remaining tributary drainages. Magnitude and timing of flow changes from these smaller tributaries could be estimated using hydrologic modeling for multiple development scenarios, though that effort is beyond the scope of the current study.

For Bear Creek, King County evaluated trends in annual peak flows in addition to the monthly maximum, monthly mean, and maximum daily flows also evaluated for Issaquah Creek. The available period of record for Bear Creek (King County 02a) was 1988 to 2011, which proved to be somewhat short to identify statistically significant trends. "However, there are indications of declining storm flows in late winter [through] early spring, and increasing storm flows during late summer through mid-winter…. Similarly, peak annual flow rates indicate a moderate upward trend…" (King County, 2012a, p. 20). Trend analyses on frequency and duration of large storms weakly suggested an increase in the number of storms with peak flows greater than 300 cfs and more strongly indicated an increase in flow duration above 400 cfs.

There is evidence that land use change contributed to increased peak flows and possibly storm volumes between the mid-1980s and the mid-1990s (Hartley and Funke, 2001), and continued development may explain some of the storm flow tendencies detected in the King County study. However, the presence of apparent trends in Bear Creek flows that are absent from Issaquah Creek may be attributable to the range of hydrologic conditions captured in the shorter Bear Creek analysis versus the longer Issaquah Creek analysis. Visual inspection of the 1988 to 2010 period in the Issaquah Creek monthly maximum daily flow rate plots in the King County study (Figure 2-1, King County, 2012a) suggests that similar weak trends might also be identified over that period for Issaquah Creek. Our examination of variability in high flow occurrences on Issaquah Creek (see Figure 6 in Section 3.2) also lends support to this explanation. Climate in the Pacific Northwest is subject to several cyclical atmospheric circulation patterns, fluctuating over periods from years to decades, so it is not unusual for periodic short-term trends to emerge (e.g., in transitioning from a dry cycle to a wet cycle) that are lost within the natural variability over a longer period.

The study also evaluated trends in frequency of lake levels exceeding a range of elevations between 27 feet and 29 feet NGVD (30.6 feet and 32.6 feet NAVD) over the period from 1965 through 2010. The study counted the number of days per water year exceeding each flow level (shown later in this report as Figure 5), and a trend analysis was performed on the number of exceedances. The study found statistically significant increasing trends at the 27.0-, 27.5-, and 28.0-foot NGVD levels that were suggested as being attributable to altered maintenance protocols (King County, 2012a). There were too few exceedances at the 28.5- and 29.0-foot NGVD levels to calculate valid statistics.

2.3 Existing Models

NHC (2010) developed an unsteady HEC-RAS model of the Sammamish River from Lake Sammamish to the mouth at Lake Washington for the Sammamish River floodplain mapping study. The HEC-RAS model was calibrated to stage and flow hydrographs at both Sammamish River gaging stations (King County 51m at the weir and USGS 12125200/King County 51t downstream) and to high water marks along the river for three flood events.

Inflows to the hydraulic model were obtained from existing HSPF hydrologic models developed in previous studies by King County and Snohomish County. The FIS study did not include recalibration of the HSPF models, though discrepancies between simulated and observed flows were noted for some locations, such as Bear Creek. These were addressed in the FIS by applying calibrated multipliers to the long-term flow hydrographs to achieve reasonable matches for lake level in Lake Sammamish and flows in the Sammamish River.

NHC reviewed the ability of these two models to consistently match observed lake levels (HEC-RAS model) and inflows from Bear Creek and Issaquah Creek (the largest tributary to Lake Sammamish).

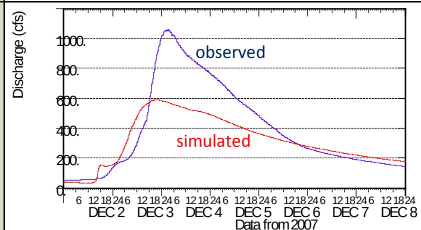
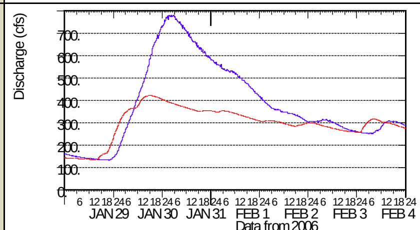
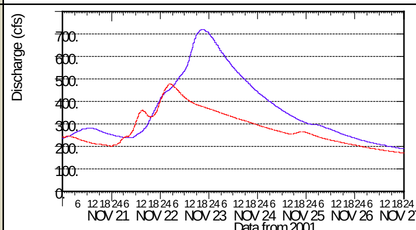
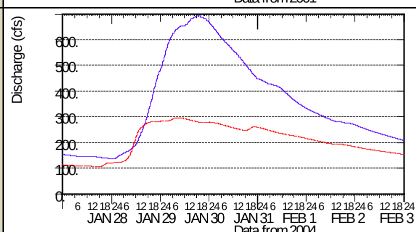
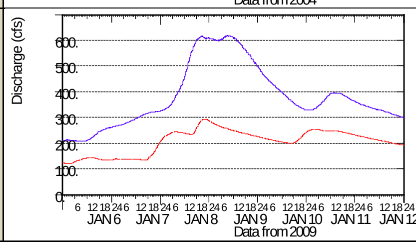
2.3.1 HSPF Models

The current HSPF models for Bear Creek and Issaquah Creek roughly simulate annual runoff volume (plus or minus ten percent) but are generally quite poor at representing specific events. HSPF-simulated flows were compared to observed flows for Bear and Issaquah Creeks for the period for which model simulations and observed 15-minute data (at King County 02a and USGS 12121600, respectively) were available. Peak timing and hydrograph duration are reasonably well-simulated for Bear Creek, as is the relative magnitude of historic events, but peak flows and event volumes are very low (Table 4), as are winter monthly volumes (Table 3). These results suggest that surface runoff is being underestimated, possibly due to too little impervious area specified in the basin model. The model designates only seven percent of the combined Bear/Evans Creek basin as effective impervious area, which seems low even for the late 1990s land use supposedly represented. A WRIA 8 screening analysis (WA DOE, 2001) estimated effective impervious percentages for the lower Bear, Evans, and Cottage Lake basins between 11 and 15 percent and upper Bear between 6 and 10 percent.

Table 3. Comparison of HSPF-simulated and observed (KC 02a) monthly volumes for Bear Creek (WY 2002-2009).

	Maximum (cfs)			Minimum (cfs)			Mean Total (AF)		
	02a	HSPF	% Diff	02a	HSPF	% Diff	02a	HSPF	% Diff
October	435	361	-17%	15.6	12.9	-17%	39.3	32.4	-18%
November	718	477	-34%	23.6	16.7	-29%	107.6	83.4	-23%
December	1055	587	-44%	28.0	18.7	-33%	150.6	125.9	-16%
January	780	420	-46%	55.1	43.5	-21%	150.3	129.9	-14%
February	583	896	54%	46.3	33.8	-27%	111.0	108.9	-2%
March	326	312	-4%	34.7	26.4	-24%	98.0	94.8	-3%
April	292	316	8%	29.1	27.0	-7%	79.4	77.4	-3%
May	158	142	-10%	21.7	21.0	-3%	46.8	42.7	-9%
June	180	111	-38%	16.4	18.8	15%	40.5	36.2	-11%
July	66	104	57%	10.0	13.9	39%	22.9	23.1	1%
August	132	106	-20%	9.2	13.1	43%	19.4	19.8	2%
September	97	149	54%	10.0	13.3	33%	22.8	20.6	-10%
Mean Annual Flow (cfs)							75.1	66.6	-11%

Table 4. Comparison of observed (KC 02a) and HSPF-simulated flows for large events on Bear Creek (WY 2002-2009). Observed flows in blue; simulated flows in red.

Date	Observed Rank	Simulated Rank	7-Day Hydrograph Comparison	Peak Flow (cfs)	Event Volume (kAF)
3-6 Dec 2007	1	2		Observed: 1055 Simulated: 587 % Difference: -44%	Observed: 4.5 Simulated: 3.4 % Difference: -26%
29-31 Jan 2006	2	7		Observed: 780 Simulated: 420 % Difference: -46%	Observed: 2.5 Simulated: 1.8 % Difference: -30%
22-25 Nov 2001	3	4		Observed: 718 Simulated: 477 % Difference: -34%	Observed: 3.5 Simulated: 2.6 % Difference: -26%
29-31 Jan 2004	4	19		Observed: 693 Simulated: 296 % Difference: -57%	Observed: 2.9 Simulated: 1.5 % Difference: -48%
8-10 Jan 2009	5	20		Observed: 619 Simulated: 293 % Difference: -53%	Observed: 2.9 Simulated: 1.4 % Difference: -51%

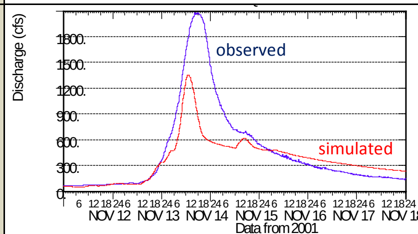
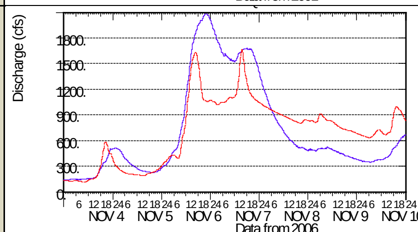
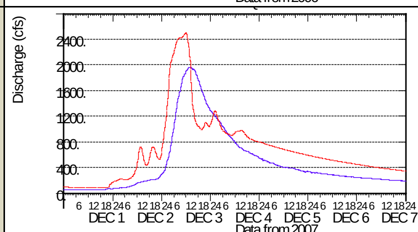
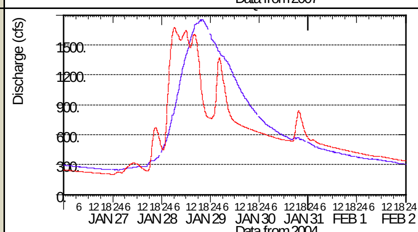
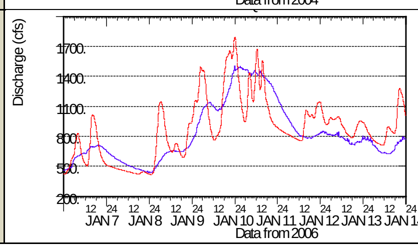
Note: cfs = cubic feet per second, kAF = 1000 acre-feet

For Issaquah Creek, which makes up roughly half of the Lake Sammamish drainage area, HSPF-simulated hydrographs do not match observed flow patterns or magnitudes well during the winter months. Winter flow volumes overall are substantially over-simulated (Table 5), as are peak flows for small to moderate events. Performance for larger events is somewhat better (Table 6), but simulated hydrographs are much spikier than observed, resulting in poor reproduction of the relative magnitude of storm events. These factors suggest that the model is producing excess surface runoff, in contrast to Bear Creek results.

Table 5. Comparison of HSPF-simulated and observed (USGS 12121600) monthly volumes for Issaquah Creek (WY 2002-2008).

	Maximum (cfs)			Minimum (cfs)			Mean Total (AF)		
	12121600	HSPF	% Diff	12121600	HSPF	% Diff	12121600	HSPF	% Diff
October	1450	603	-58%	11.0	15.8	44%	55.0	53.9	-2%
November	2080	2017	-3%	17.0	15.7	-8%	166.8	185.3	11%
December	1970	2500	27%	23.0	21.9	-5%	214.3	252.0	18%
January	1750	2207	26%	44.0	63.2	44%	280.9	315.4	12%
February	720	1487	107%	57.0	48.3	-15%	171.3	204.5	19%
March	1120	1473	32%	44.0	36.2	-18%	170.5	211.9	24%
April	983	1942	98%	44.0	47.6	8%	134.3	156.4	16%
May	670	806	20%	26.0	30.1	16%	81.1	83.8	3%
June	279	1022	266%	24.0	27.1	13%	62.7	55.7	-11%
July	87	126	45%	12.0	17.0	41%	29.7	26.8	-10%
August	422	238	-44%	9.2	13.7	49%	24.0	22.3	-7%
September	168	165	-2%	6.2	13.7	122%	27.3	27.4	0%
Mean Annual Flow (cfs)							119.7	134.0	12%

Table 6. Comparison of observed (USGS 12121600) and HSPF-simulated flows for large events on Issaquah Creek (WY 2002-2008). Observed flows in blue; simulated flows in red.

<table>
<tr><th>Date</th><th>Observed Rank</th><th>Simulated Rank</th><th>7-Day Hydrograph Comparison</th><th>Peak Flow (cfs)</th><th>Event Volume (kAF)</th></tr>
<tr><td>14-16 Nov 2001</td><td>1</td><td>28</td><td>
</td><td>Observed: 2080
Simulated: 1352
% Difference: -35%</td><td>Observed: 5.2
Simulated: 3.5
% Difference: -33%</td></tr>
<tr><td>6-8 Nov 2006</td><td>2</td><td>10</td><td>
</td><td>Observed: 2080
Simulated: 1199
% Difference: -46%</td><td>Observed: 7.1
Simulated: 5.8
% Difference: -19%</td></tr>
<tr><td>2-4 Dec 2007</td><td>3</td><td>1</td><td>
</td><td>Observed: 1970
Simulated: 2500
% Difference: 27%</td><td>Observed: 4.7
Simulated: 6.0
% Difference: 27%</td></tr>
<tr><td>29-31 Jan 2004</td><td>4</td><td>9</td><td>
</td><td>Observed: 1750
Simulated: 1673
% Difference: -4%</td><td>Observed: 5.8
Simulated: 5.3
% Difference: -8%</td></tr>
<tr><td>9-12 Jan 2006</td><td>6</td><td>6</td><td>
</td><td>Observed: 1500
Simulated: 1792
% Difference: 19%</td><td>Observed: 7.9
Simulated: 8.1
% Difference: 2%</td></tr>
</table>

Note: cfs = cubic feet per second, kAF = 1000 acre-feet

Recalibration of the Issaquah Creek and Bear Creek models is strongly recommended if further analysis of peak flows, high flow durations, or storm volumes is needed to support an updated design hydrology. Though the scaling approach used in the FIS was suitable for the targeted storm event modeling, Willowmoor project design will likely need to consider system response over a wider range of flows , and potentially future conditions scenarios, where relative watershed response may change. Given the importance of Bear Creek flows to the hydraulic capacity of the system (see Sections 2.2.1 and 3.2), ability to simulate peak flows and hydrograph timing from Bear Creek is likely to be critical to any further modeling analysis to support the project design. Based on the results of calibration of the

Issaquah and Bear Creek models, there may be systematic adjustments that could also be applied to the East and West Lake Sammamish Tributary models, for which only limited calibration data are available.

2.3.2 HEC-RAS Model

The HEC-RAS model was constructed to simulate general conditions from Lake Sammamish to Lake Washington for an approximately 60 year period. Figure 2 shows the simulated results for a portion of this time, from water year 1998 to 2009, at the Marymoor Weir gage location (King County gage 51m) compared to measured stage at the same location and also upstream in Lake Sammamish (USGS station 12122000). Typically, USGS-recorded lake stage at the south end of the lake is a few tenths higher than the water level at the weir.

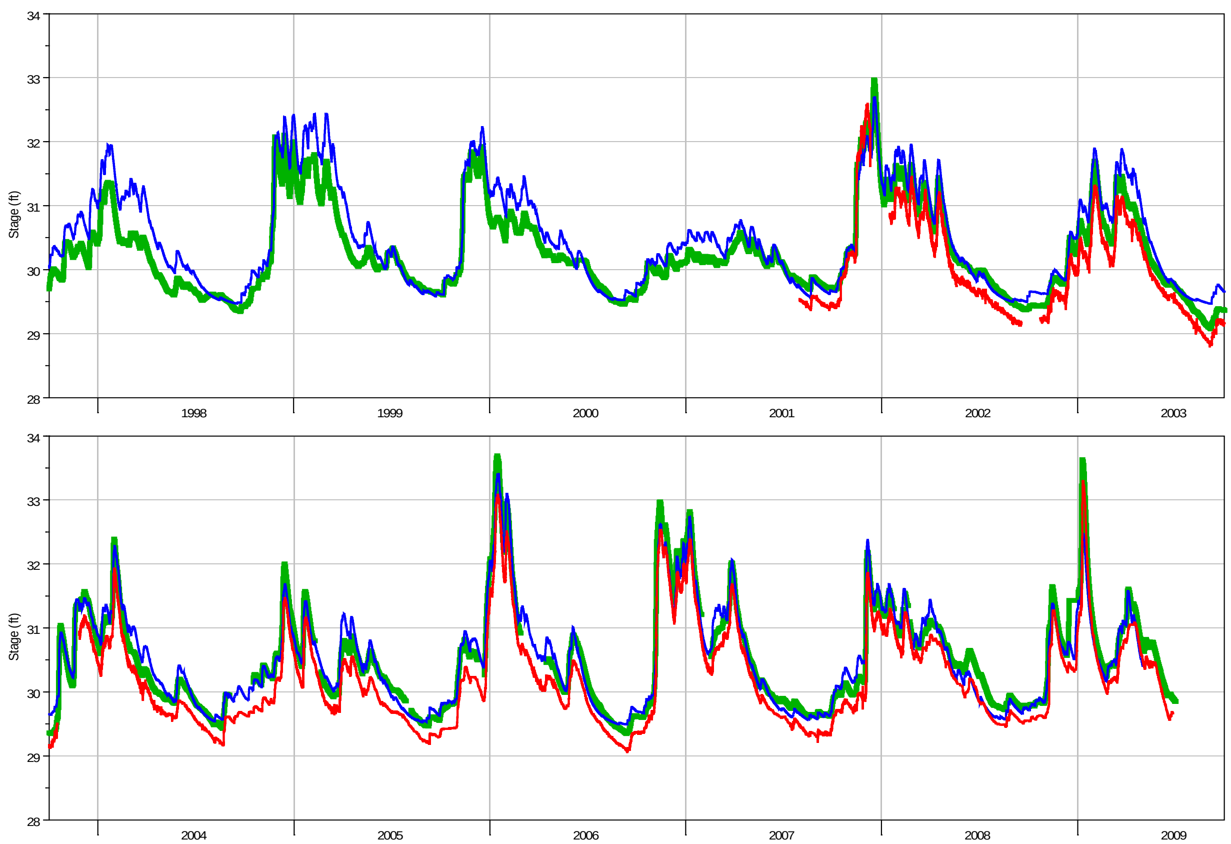


Figure 2. Water levels simulated at the Marymoor weir in blue, recorded at King County 51m in red, and observed USGS Lake Sammamish gage 12122000 in green.

Simulated results are generally within a couple of tenths of a foot of the observed weir stage from WY 2004 through WY 2009, though there are some simulated excursions of close to a foot. The existing model uses one static set of model parameters (e.g., channel vegetation and weir conditions) to represent a range of flows while ensuring that peak stages are reasonably matched for the entire 60 year period. When specifying this set of model parameters during WY 2003 and earlier, the model tends to simulate stage slightly higher than that in Lake Sammamish as the physical conditions of the TZ vary from that represented in the model. During this earlier time period, the hydrologic simulation of inflows tends to overpredict observed flows (when compared at downstream gage 51t), possibly further contributing to the higher-than-observed weir stage.

The TZ is a relatively complex section to simulate. Vegetation conditions have changed over time both naturally (e.g., growth of willows over the channel and grasses in the overbanks, seasonal growth and die-back) as well as through TZ maintenance (e.g., mowing). Channel roughness, both horizontally and vertically, can be altered in the model to match the changing TZ conditions. In addition, the weir has a narrow notch for low flow conditions and a much wider crest for high flows. Vegetation affects the efficiency of the weir. Preliminary indications show that by adding additional weir details to the model and adjusting roughness values to represent the specific conditions during a period of interest, the model can simulate results generally closer than the existing model. The model simulation also shows that Bear Creek can cause a backwater through the TZ. If model refinements are made, the accuracy of the modeled backwater effect could be investigated.

The purpose of the HEC-RAS modeling for the FIS was to simulate stage and flow well along the entire Sammamish River from Lake Sammamish to Lake Washington. For purposes of the Willowmoor project, model refinements could focus on more closely replicating the reach between Bear Creek and Lake Sammamish.

3 Statistical Analysis

NHC performed statistical analysis on currently available observed and simulated data to establish a current hydrologic context, to compare against the original design flows, to evaluate coincidence of high flows and high lake levels, and to identify trends in hydrology that could affect project function. This work builds on the statistical analysis already performed by the County and documented in the *Findings on Lake Sammamish Outflow* (2012a) report. The analyses focus on annual data and trends, rather than just the spring season, because winter flooding has become a greater concern with development of the formerly agricultural Sammamish River valley.

3.1 Corps Design Flows

As discussed in Section 2.1, the TZ was originally designed to contain a 1,500 cfs spring flow with lake levels not to exceed 29.0 feet NGVD (32.6 feet NAVD). The design conditions were based on the March 1950 event, which was characterized as having a 10-year annual and 40-year spring (after March 1) recurrence interval. As mentioned previously, the Corps' original frequency analysis was not available for review. It seems likely that it would have been based on the flow record for the Sammamish River near Redmond gage (USGS 12125000), which extends from 1940 through 1957. Annual frequency analysis of that dataset using the methods of Bulletin 17B (USGS, 1981) produces a 10-year annual peak flow estimate of 1,250 cfs. The 1,500 cfs design flow is within the 95-percent confidence limits, as is the 1,360 cfs peak flow from March 1950.

Based on post-1966 observed data for the Sammamish River near Woodinville (USGS 12125200 and King County 51t), the statistical 10-year annual flow and 40-year spring flow are substantially higher than the Corps design flow (Table 7). The 1,500 cfs design flow for the Sammamish River below Bear Creek equates to approximately a 3-year annual flow and just over a 10-year spring flow based on observed peak flows since 1966. HSPF-simulated flows for this location (NHC, 2010) show similar results to the observed. Table 7 shows frequency analysis results for the common period for simulated and observed data from water year 1966 through 2009. Extension of the analysis to the full period available for each dataset (1966 through 2013 for observed, 1949 through 2009 for simulated) affects 10-year flow estimates by less than two percent.

Table 7. Flow frequency analysis for Sammamish River near Woodinville (1966-2009)

	Location	10-Yr Annual Flow (cfs)	40-Yr Spring Flow (cfs)	1,500 cfs Recurrence Interval (yrs)	
				Annual	Spring
Observed	12125200/51t	2,150	1,990	2.9	11
Simulated	RAS XS 50090	1,970	2,090	2.9	11

A number of factors could contribute to the substantial increase in Sammamish River flows since the original design analysis, but it seems most likely that the project itself is the major cause. As King County has demonstrated in previous studies (e.g., King County, 2010 and 2012b), there have been no significant climate trends affecting precipitation or streamflow over this period. Increased flows due to watershed development (particularly in Bear Creek) do not appear to have had a significant impact on the Sammamish River peak flow record, as there is no apparent increasing trend over time since 1966. A relatively short record at the time of the Corps analysis could affect frequency estimates, particularly if that period lacked very large events. However, analysis of various 15 to 20 year periods in the Sammamish River near Woodinville record, including comparing the wettest and driest periods, produced differences in the 10-year flow on the order of five to ten percent, compared to a 33 percent increase over the Corps design flow. Thus, it seems likely that increases in the capacity of the lake outlet and downstream channel due to construction of the Sammamish River project are responsible for increased peak flows.

The Corps design documents do not specify a frequency for the design flow on Bear Creek (690 cfs), and because of lake storage effects, frequency of a particular event is likely to be different on the Sammamish River and Bear Creek. For purposes of comparison, however, frequency analysis was conducted on the continuous record of observed data for Bear Creek (King County 02a; WY 1989-2013) and indicated a 10-year annual flow of 1,150 cfs and a 40-year spring flow of 730 cfs. Both of these are higher than the March 1950 peak of 650 cfs. Adding the six peaks from the USGS record for Bear Creek (station 12124500) between 1946 and 1958 to the annual frequency analysis decreases the 10-year flow by about 35 cfs. On this augmented frequency curve, the March 1950 event has an annual exceedance probability of about 0.25 (i.e., a four-year recurrence interval). It should be noted that the Bear Creek design flow is not equivalent to the Bear Creek contribution to the Sammamish River design flow, as the latter[7] represents Bear Creek inflow coincident with the lake outflow peak and would typically be less than the peak flow for a given event.

It appears that the Corps project has had the effect of increasing high flows in the Sammamish River due to increased lake outlet and channel capacity. Despite a substantial increase in the 10-year flow since construction of the weir and TZ, however, prior modeling (NHC, 2010) indicates that the TZ and downstream Sammamish River channel have sufficient capacity to contain the current 10-year event, with the possible exception of the area between approximately NE 90th Street and NE 145th Street. In many areas, the currently estimated 50-year and even 100-year flows remain within the channel.

3.2 Lake Level Analysis

The other objective of the Sammamish River project was to keep Lake Sammamish levels below 29.0 feet (NGVD) for the project design event while maintaining minimum (summer) levels. In recent years, however, lakeside homeowners have expressed concerns about higher lake levels and more frequent flooding. This study examined the post-project lake level record and analyzed trends in high and low lake

[7] Assumed to be 300 cfs in previous work by the Corps and King County

levels relative to other hydrologic and hydraulic influences. NHC also assessed correspondence between inflows, downstream channel conditions, and lake levels during extreme events to characterize the factors contributing to the highest lake levels.

The full record (1939 through 2013) of Sammamish River lake levels is shown in Figure 3. Vertical lines indicate completion of the Sammamish River project in 1964 and modification of the weir in 1998. The impact of the original project on the annual range of lake levels is immediately apparent. Also notable is the apparent shift in annual minimum lake levels since the 1998 weir modifications. The post-project trends are explored further in the following sections.

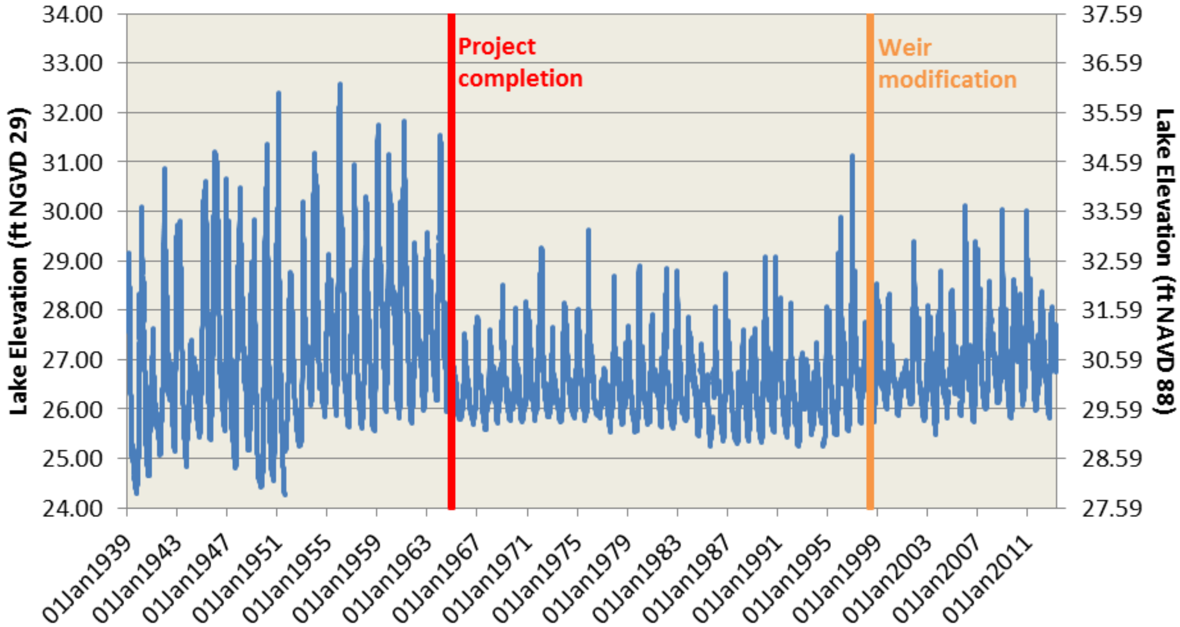


Figure 3. Time series of daily Lake Sammamish elevations.

The post-project (1965 through 2013) daily records for Lake Sammamish elevation and Issaquah Creek streamflows are displayed in Figure 4. In this figure, the horizontal axis shows the day of the water year, while the vertical axis shows the water year. Colors indicate streamflow or stage values measured on each day, while white indicates missing values. The color thresholds for the two plots, which are based on lake levels of interest, reflect the same duration exceedance levels for both records from 1965 through 2013. For example, lake level exceeds 26 feet NGVD (29.6 feet NAVD) approximately 76 percent of the time since 1965, so the corresponding Issaquah Creek threshold (38 cfs) was determined by finding the daily flow that was exceeded 76 percent of the time over the same period.

We see that, in general, the relative magnitudes of lake level and Issaquah Creek flow are consistent, at least through the mid-1990s, which is expected since Issaquah Creek accounts for over half of the drainage area to the lake. For example, the period from 1965 through 1976 appears as wetter (more blues on both plots), while 1985 through 1996 is drier (more greens). Lake levels are notably more sustained than streamflows at a given level, indicated by the longer stretches of continuous color, which is indicative of the longer response time of the relatively large storage provided by the lake.

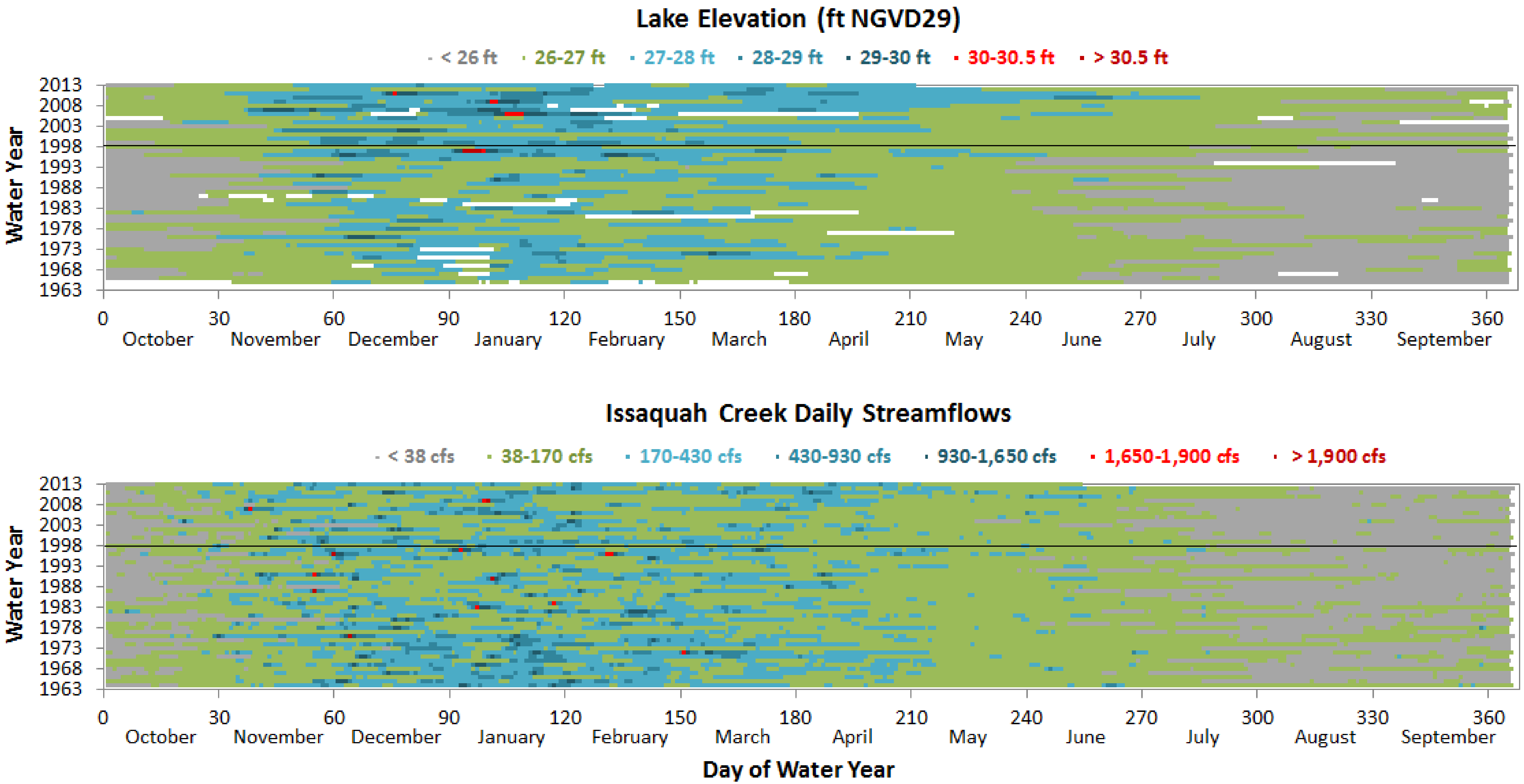


Figure 4. Daily records of lake elevation (feet NGVD) and Issaquah Creek flow. The values on the horizontal axis are day of the water year (October through September). Colors indicate streamflow or stage values. White indicates missing values.

The most notable difference between the two records in Figure 4 is the distinctly higher lake levels, relative to streamflows, since the late 1990s or early 2000s, indicated by the higher concentration of "blue" lake levels. Note that the threshold for the light blue lake level in Figure 4 corresponds to the regulatory OHW level of 27 feet NGVD (30.6 feet NAVD), so the record indicates much more frequent excursions above that level in the past ten to fifteen years. It is likely not a coincidence that the shift in lake levels relative to Issaquah Creek streamflows appears to correspond to the modifications to the lake outlet weir in 1998 (see the horizontal black line on Figure 4 plots). Since that time, lake level has exceeded 27 feet approximately 37 percent of the time, compared to approximately 24 percent over the entire post-project period (1965 through 2013). In contrast, Issaquah Creek has exceeded the corresponding 170 cfs threshold 23 percent of the time since 1998, consistent with the historical average. If the lake level change was driven by wetter conditions in general, we would expect to see a similar signal in the Issaquah Creek streamflows.

Absent additional data or further investigation, we believe it is reasonable to consider Issaquah Creek flows as representative of inflow volumes to the lake and thus inflow contributions to lake levels. Flow increases have likely occurred on smaller tributaries with increased development over the past 20 to 30 years, particularly on the Sammamish Plateau. However, given the relatively small size of affected areas compared to the entire lake drainage basin and the tendency for peak flow increases to be larger than storm volume increases (e.g., Hartley and Funke, 2001), it seems unlikely that this effect would have a significant impact on lake volumes during large events.

3.2.1 Exceedance Analysis

In a previous analysis, King County (2012a) found no evidence of increasing trends in mean or peak streamflows for Issaquah Creek (see Section 2.2.2). However, the same study noted an increasing trend in high lake level exceedances, i.e., the number of days the lake level exceeded a given threshold, for Lake Sammamish between 27 and 28 feet NGVD (Figure 5). The study noted that there were no significant trends in lake level exceedances from 1965 through 1991, when changes to the TZ maintenance protocols were implemented. In this study, NHC confirmed that there is a similar lack of statistically significant exceedance trends through 1998, when weir modifications occurred. The period of record since 1998 is too short for statistical trend analysis, but we hypothesize that trends may be similarly absent in the post-1998 period, indicating a shift in lake levels rather than an increasing trend.

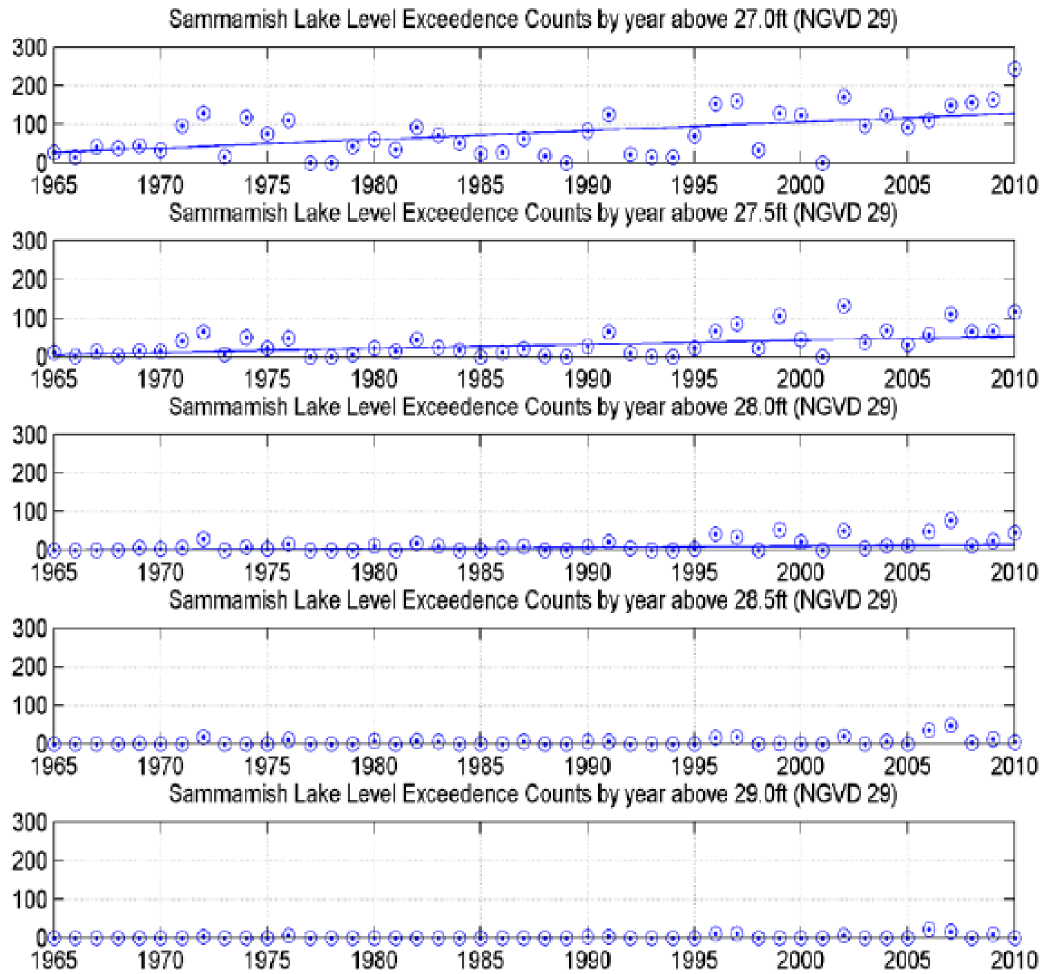


Figure 5. Number of days each year that Lake Sammamish elevation exceeded a given lake level for WY 1965 through 2010 (Figure 4-1 in King County, 2012a).

For this study, NHC conducted a similar daily exceedance analysis on the daily streamflow record for Issaquah Creek to look for trends in the frequency of high flows. To correspond with the thresholds in Figure 4, NHC determined the number of days exceeding flow thresholds of 170 cfs, 430 cfs, and 930 cfs in each water year of the record. Results, shown in Figure 6, reveal no apparent trends in these metrics over time. With no apparent climatic trend corresponding to increasing periods of high lake levels, it seems likely that changing hydraulics through the weir and TZ are playing a significant role.

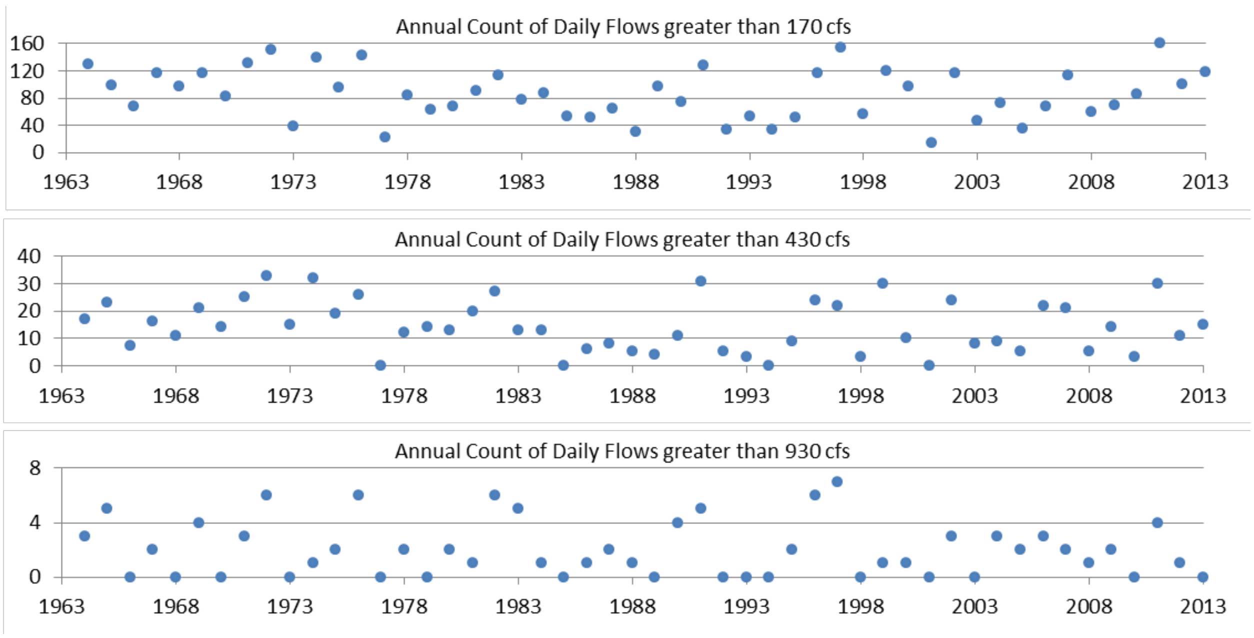


Figure 6. Number of days each year that Issaquah Creek daily flows exceeded a given flow level for WY 1964 through 2013.

3.2.2 Lake Level Trends

To further explore how various lake levels have changed over time, NHC examined a range of statistical annual lake levels, including the annual maximum, mean, and minimum levels, for the period from 1965 through 2013 (Figure 7).

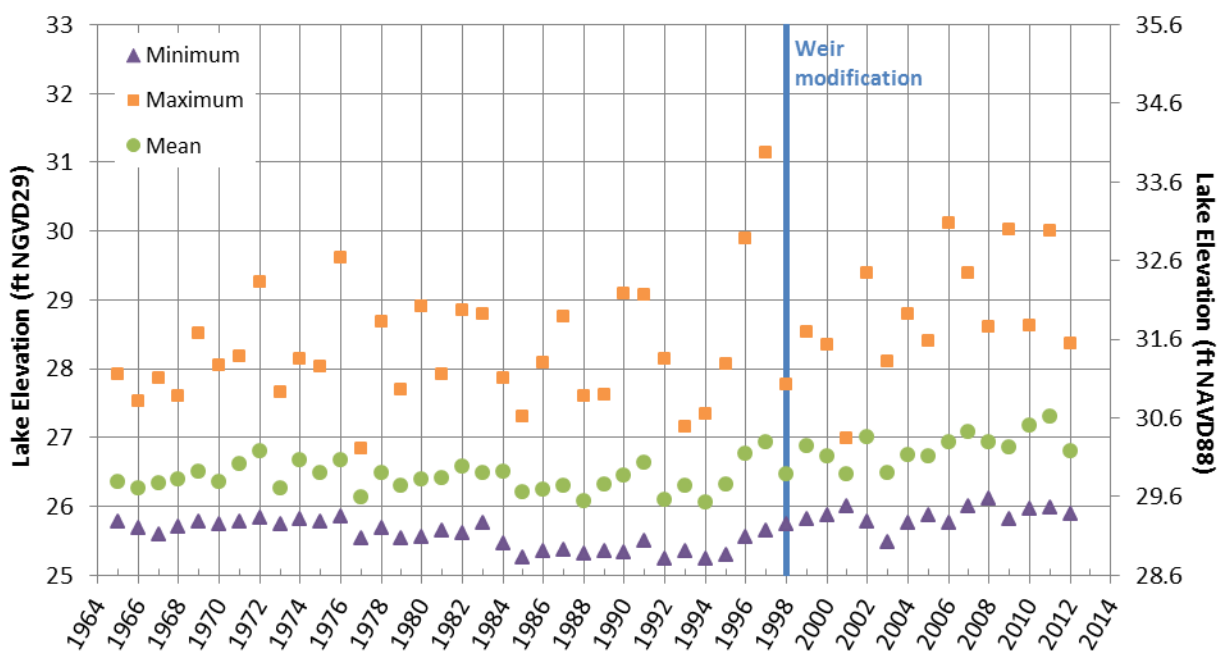


Figure 7. Annual distribution of daily lake stage. Minimum, mean, and maximum daily values are plotted for each water year.

Statistical trend analyses (using the Mann-Kendall test) indicate significant decreasing trends from the annual minimum (99.9 percent confidence) up to the 25th percentile[8] (99 percent confidence) lake levels from 1965 through 1997. No statistically significant trends were detected at the 90 percent confidence level for median and higher lake levels over the same period. The low lake level trends correspond with significant decreases in late summer flows on Issaquah Creek, reported previously by King County (2012b) and confirmed in this study. The observed decline in low lake levels appears to have been counteracted by the weir modifications in 1998, as minimum lake elevations have increased while late summer streamflows have remained at lower levels.

Statistical tests of data homogeneity were also conducted on the multiple lake level quantiles. The purpose of these tests is to determine whether a series of data belong to the same statistical population (i.e., they are homogeneous) or at what point there is a statistical break (or inhomogeneity) in the data, which would suggest a change in external influences. Results from three different tests were not entirely consistent across the various lake level quantiles, but all indicated significant breaks (at the 95 percent confidence level) in the mean and median levels between 1995 and 1997. Two of the three tests found significant breaks in the other quantiles as well. In all three tests, results for maximum flows had the lowest significance but consistently showed similar patterns of results.

Initially, it is somewhat counterintuitive that the homogeneity tests tend to identify 1995 or 1996 as the break point in most of the lake level quantiles, as we are not aware of any significant changes to the system at that time. However, water years 1996 and 1997 were exceptionally wet and produced two of the largest events, for both lake level and streamflow volume, in the record (February 1996 and January 1997). Figure 8 shows the daily lake elevations for water years 1996 and 1997 compared to long-term daily average elevations from 1965 through 1995 and 1998 through 2013. The intent of Figure 8 is to illustrate the annual pattern of flows. The difference in the two long-term daily averages is notable but not necessarily a reliable indicator of the magnitude of change between the two periods.

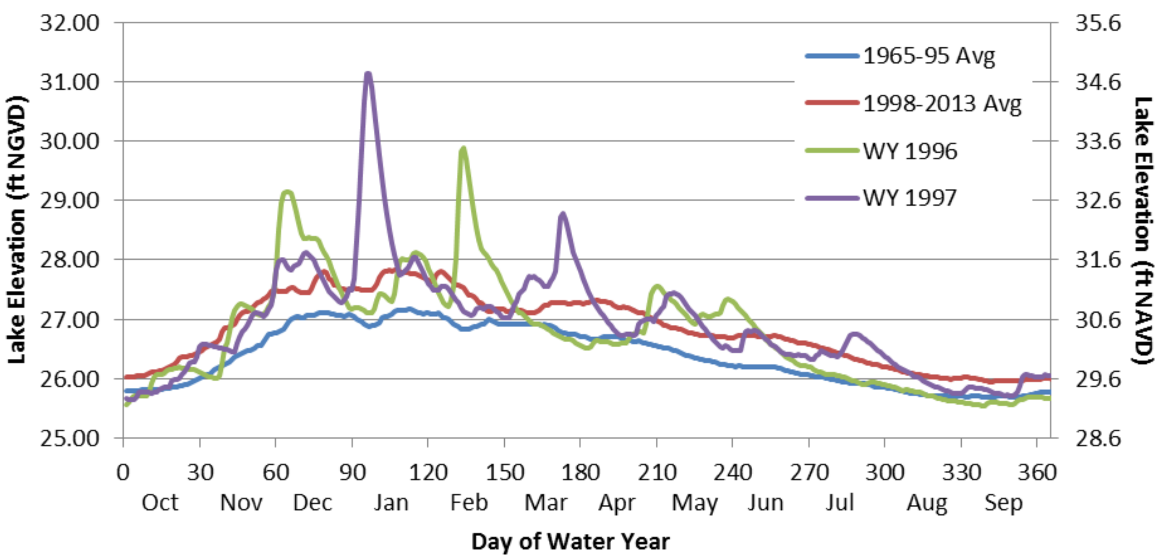


Figure 8. Comparison of 1996 and 1997 lake levels to long-term daily average levels. Horizontal axis is day of water year (October through September).

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[8] The “x” percentile level is determined by ranking the daily lake levels for each water year in order of magnitude and selecting the value for each year that corresponds to the lowest “x” percent of the days, i.e. lake levels were below the 25th percentile value on 25 percent of the days in a given year (and exceeded it on 75 percent of the days).

Figure 8 shows that the 1996 and 1997 water levels are clearly well above the 1965 through 1995 average in general, but inter-event levels still tend to drop to the earlier (i.e., pre-weir modification) pattern. Given this, it seems likely that it is an accident of timing—with two wet years preceding the weir modifications—rather than a systematic shift that places the break prior to the weir modifications. Indeed, if we move water years 1996 and 1997 earlier in the record (to separate them from the changes in 1998) the homogeneity tests do not indicate a significant break in any lake level quantiles at that point (i.e., those years fall within the acceptable variability) and uniformly identify the most significant break at 1997/1998. In any case, the results of these tests certainly support the idea that lake levels since the mid-1990s are distinctly different than 1965 through 1995 levels, especially at low to moderate elevations.

Detailed documentation and results from the trend analyses performed for this study are provided in Appendix A to this report.

3.3 Extreme Lake Level Events

Lake Sammamish elevation has surpassed the benchmark of 29 feet NGVD (32.6 feet NAVD)—the flood control elevation specified in the original design objective—in 16 separate events (with dates ranging from November through March) since construction of the Sammamish River project. Since 1965, the chance of exceeding 29 feet NGVD in a given year is approximately 20 percent (or a five-year annual recurrence). Fourteen of the sixteen events occurred since 1989, and nine since 1998. The lake has surpassed 30 feet NGVD (33.6 feet NAVD) four times, all in the most recent half of the record with the earliest in water year 1997. Three of the four occurred in the month of January and one in December. The January 1997 event produced the highest lake level on record, 31.14 feet NGVD (34.73 feet NAVD) in the daily record. This was a large rain-on-snow event in the Puget Sound lowlands that produced peaks of record on many streams in the region.

To explore likely causes for the highest lake level events, we examine the records of the top seven events. Table 8 presents these seven events, ordered by rank. The Issaquah Creek daily hydrograph and the daily lake elevation values are plotted. Fifteen-minute hydrographs are available for four of these events and are plotted as well. The fifth and sixth columns of Table 8 show the rank of each event with respect to one-day and three-day peak inflows from Issaquah Creek. The last column shows the associated peak inflow from Bear Creek and its rank; ranks reflect only the Bear Creek period of record from 1988 through 2013.

Although several of these seven lake level events coincide with some of the highest recorded peak inflow events, others are coincident with rather unremarkable inflow peaks. For example, the third highest recorded elevation event (January 11-21, 2006) was associated with a peak inflow that ranked only eighteenth. While they are necessary to cause a high lake level, neither peak daily inflow nor total inflow volume is sufficient, on its own, to account for the most extreme lake level events.

Based on the individual event characteristics (column 4 of Table 8), differing explanations are proposed as likely for the extreme lake elevations.

1. January 1-9, 1997. The most extreme lake level event is explained by an exceptionally prolonged intense event, lasting over six days, which produced the highest Bear Creek discharge on record (reaching 1,500 cfs on December 31, 1996). None of those days had a comparably extreme inflow from Issaquah Creek (the event ranked ninth for its peak daily inflow).
2. December 13-19, 2010. The second highest lake level event was neither exceptionally prolonged nor had a comparably extreme inflow. The likely explanation for that event is a

reduced discharge rate from the lake again caused by exceptionally high discharge from Bear Creek (approaching 1,400 cfs).

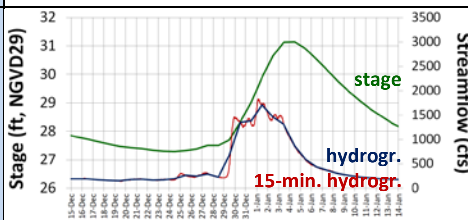
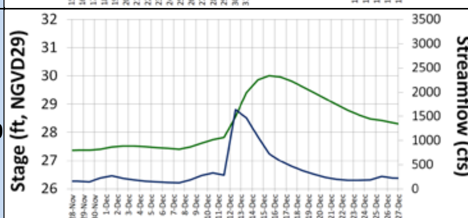
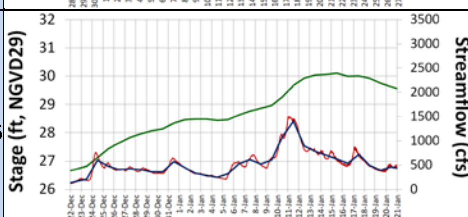
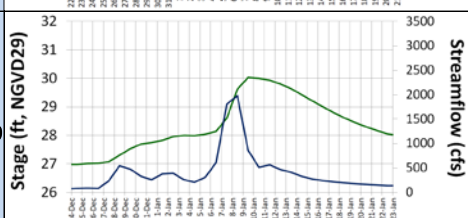
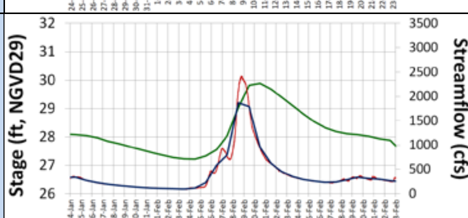
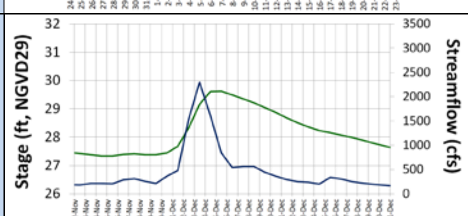
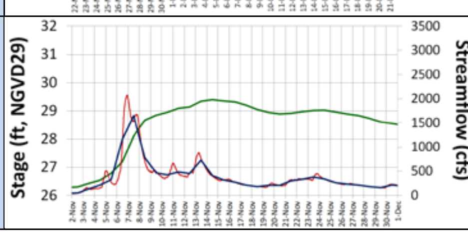
3. January 11-21, 2006. For the third-ranking lake level event, the likely explanation is yet a different one. It appears that a series of smaller events built up lake levels, which already approached 29 feet NGVD (32.6 feet NAVD) when the relatively moderate peak streamflow arrived and filled the lake beyond the 30-foot (NGVD) level.

4. January 8-14, 2009. The fourth ranking lake level event is likely explained by the occurrence of an extremely high peak daily inflow at a time when a series of smaller events, including melt from an unusually high lowland snowpack, had built up lake levels past the 28-foot (NGVD) mark.

5 & 6. February 8-12, 1996 and December 4-6, 1975. The fifth and sixth ranking lake stage events both had a combination of extremely high peak inflows and a prolonged duration of high inflows.

7. November 14, 2006. Neither Issaquah nor Bear Creek inflows were remarkable for the seventh ranking lake stage event. Combined with the sustained very high lake levels, which remained in the vicinity of 29 feet NGVD (32.6 feet NAVD) for about three weeks, this suggests reduced outlet capacity, perhaps due to heavy vegetation in the TZ.

Table 8. High Lake Sammamish events ordered by rank of peak lake elevation, indicated in the first column. Columns 5 and 6 give the event's rank with respect to peak daily and 3-day flows on Issaquah Creek (for 1976-2013). The last column gives the associated Bear Creek peak flow and rank in the Bear Creek record (1988-2013).

Lake Level Rank	Date	Lake Sammamish Stage at Weir and Issaquah Creek Hydrograph	Event Characteristics	Daily Inflow Ranks		Bear Cr Peak Q (Rank)
				Peak	3-day	
1	Jan 1-9, 1997		This event generated the highest of all recorded lake stage values (31.14 ft). The peak daily flow from incoming Issaquah Creek was not as exceptional but the event was **prolonged**, lasting over 6 days. **Bear Ck discharge** was highest in record, impairing lake rating curve.	8	4	1572 cfs (2)
2	Dec 13-19, 2010		Daily peak flow from incoming Issaquah Creek was not as extreme, though 3-day inflows were high, and the event was not exceptionally prolonged (about 4 days long). **Backwater due to high Bear Ck discharge** is suspected as the cause for the exceptionally high stage.	12	7	1068 cfs (3)
3	Jan 11-21, 2006		Daily peak flow from incoming Issaquah Creek was unremarkable but the event followed a **series of smaller events that built up lake levels** over the preceding weeks.	18	13	587 cfs (13)
4	Jan 8-14, 2009		This event had **extremely high inflows from Issaquah Creek** and the event followed a **series of smaller events that built up lake levels** over the preceding 10 days.	5	2	619 cfs (11)
5	Feb 8-12, 1996		This event had **extremely high inflows from Issaquah Creek** and was **prolonged**, lasting about 7 days.	6	3	941 cfs (5)
6	Dec 4-6, 1975		This event had the **second highest peak inflow from Issaquah Creek** and was **prolonged**, lasting over 5 days.	2	1	n/a
7	Nov 14, 2006		This event had **moderately high inflow from Issaquah Creek**, and was **followed by several smaller events that kept lake stage at a high level** for about 3 weeks.	11	11	329 cfs (73)

It is apparent from the above discussion that inflow volume is not the sole driver for extreme lake level events (i.e., events where lake level exceeds 29 feet NGVD), or we would expect to see much closer correspondence between the highest inflow volumes and highest lake levels. The magnitude and timing of Bear Creek flows, in particular, have a demonstrated impact on lake outflows and elevations (e.g., King County, 2012a). Figure 9, below, shows a time series of lake elevations (in feet NGVD); peak flows on Bear Creek and the Sammamish River near Woodinville exceeding the respective 300 cfs and 1,500 cfs design values; and three-day mean flows on Issaquah Creek exceeding 1,000 cfs. The Issaquah Creek flows are included as a proxy for lake inflow volume, and the 1,000 cfs threshold corresponds with the approximately 2.5-year return period of the 1,500 cfs Sammamish River flow (Table 7).

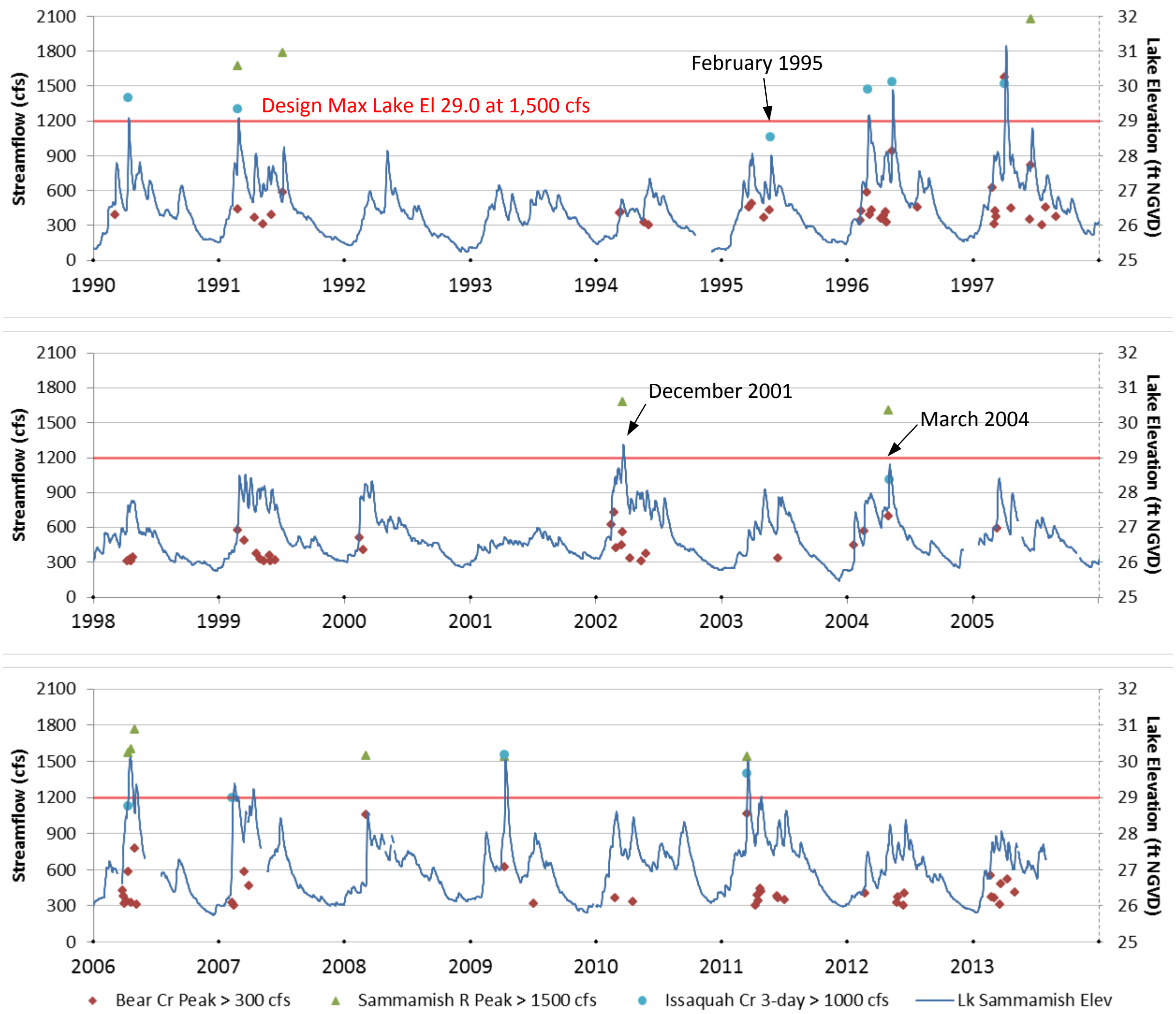


Figure 9. Time series plot of lake elevations, Bear Creek and Sammamish River peaks above design values, and maximum Issaquah Creek three-day mean flows representing inflow volume to the lake. Horizontal axis labels are water years (October through September).

We can see that inflow volume does, indeed, have the strongest correspondence with extreme lake levels—all extreme lake level events except December 2001 correspond to a high three-day Issaquah Creek flow. However, it is not as strong a predictor of relative magnitude of the peak lake level; i.e., the highest three-day Issaquah Creek flows do not correspond with the highest lake levels. This agrees with the information presented in Table 8. Most of the extreme lake level events also coincide with high flows from Bear Creek, which is not unexpected since the same storms generally affect the Issaquah and Bear Creek basins. High Sammamish River flows occur almost exclusively in events with high Bear Creek flows and about equally with lake levels above and below 29 feet NGVD (32.6 NAVD) (though exclusively above OHW levels—between 27 and 28 feet NGVD).

As shown in Figure 9, February 1995 and January 2004 are the only high inflow events in the past 25 years that did not correspond with extreme lake levels. January 2004 also exceeded the Bear Creek and Sammamish River thresholds. Notably, both of these events followed mowing of the TZ (Table 2). Lake level also has not exceeded 29 feet NGVD since mowing in 2011—despite more than a dozen high Bear Creek flows—though there have been no high Issaquah Creek events during that period. This suggests that vegetation management in the TZ has a role in maintaining hydraulic capacity of the lake outlet to maintain lake elevations within target levels (see Figure 1).

It is notable that nearly 90 percent of the highest (at least 29 feet NGVD) post-project lake level events have occurred since 1990, while only about half of the highest Issaquah Creek events have occurred in that time, as shown in Figure 10. Since that time, we see close to a one-to-one correspondence of high Issaquah Creek events with high lake events, suggesting that there has been a change in the relationship between lake level and Issaquah Creek flow volume for large events.

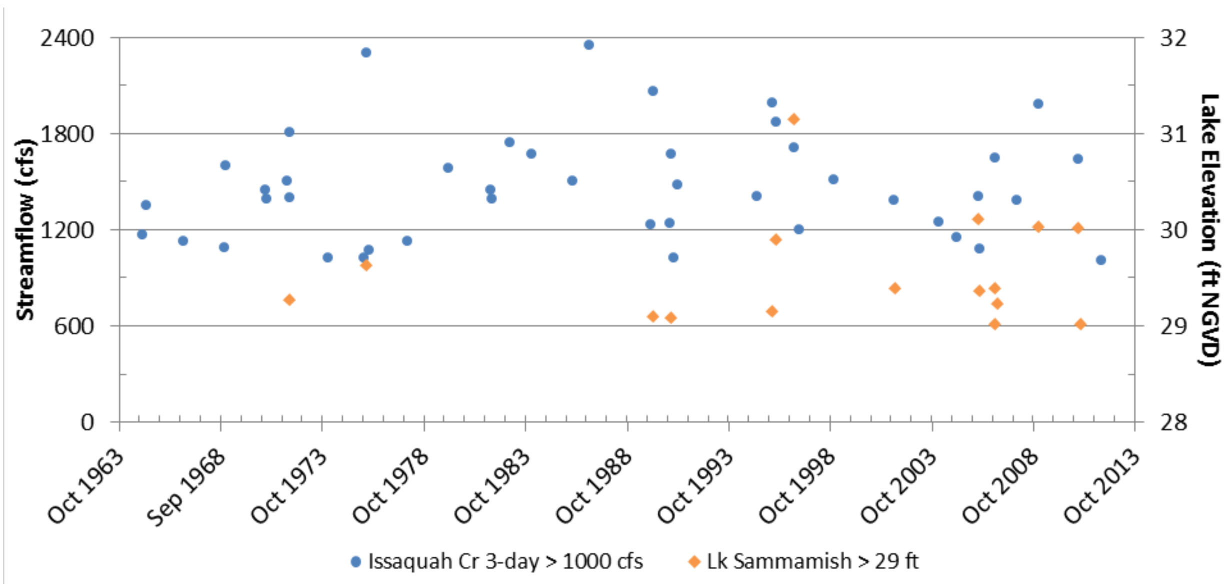


Figure 10. Comparison of high Issaquah Creek flow events and high Lake Sammamish stage events (1965-2013)

Since we don't think that potential flow increases from other tributaries are likely to have significantly affected inflow volumes in large events (requiring relatively more storage than in the past), this points to reductions in lake outlet capacity as a cause for relatively more frequent high lake levels. We have already identified several potential causes of reduced lake outflows, including weir modifications, vegetation in the TZ, and backwater from Bear Creek. Interestingly, the original annual maintenance regime for the TZ was discontinued in 1989. The Bear Creek backwater effect is discussed further in the following section.

3.3.1 Lake Elevation-Discharge

As discussed in the previous section, two of the top seven extreme lake level events (January 1-9, 1997 and December 13-19, 2010) appear to have been partly explained by a somewhat impaired stage-discharge curve caused by high discharges from Bear Creek. This section takes a closer look at the evolution of the lake's stage-discharge relationship over time, in recent decades.

Figure 11 shows the relationship between mean daily lake discharge and mean daily lake elevation since 1988. The daily time scale is used, rather than hourly, because the daily datasets cover longer periods of record and the daily scale is sufficiently detailed for the purposes of the present analysis. Lake discharges were estimated indirectly to make discharge independent of stage at the weir to facilitate exploration of variability in stage-discharge over time. Lake discharge was estimated from daily streamflow records for the Sammamish River and Bear Creek using a relationship developed by King County (2012a, page 26):

$$Q_{Lake\ outflow} = Q_{Woodinville} - 1.2\ Q_{Bear\ Creek,\ Redmond}$$

The Sammamish River streamflow record comes from USGS gage 12125200 and from King County gage 51t, which replaced the USGS station in 2005. The Bear Creek streamflow record is that for King County 02a gage. In Figure 11, marker color is used to differentiate between sub-periods generally corresponding to the rating curve periods shown in Figure 1, as well as a pre-weir modification period.

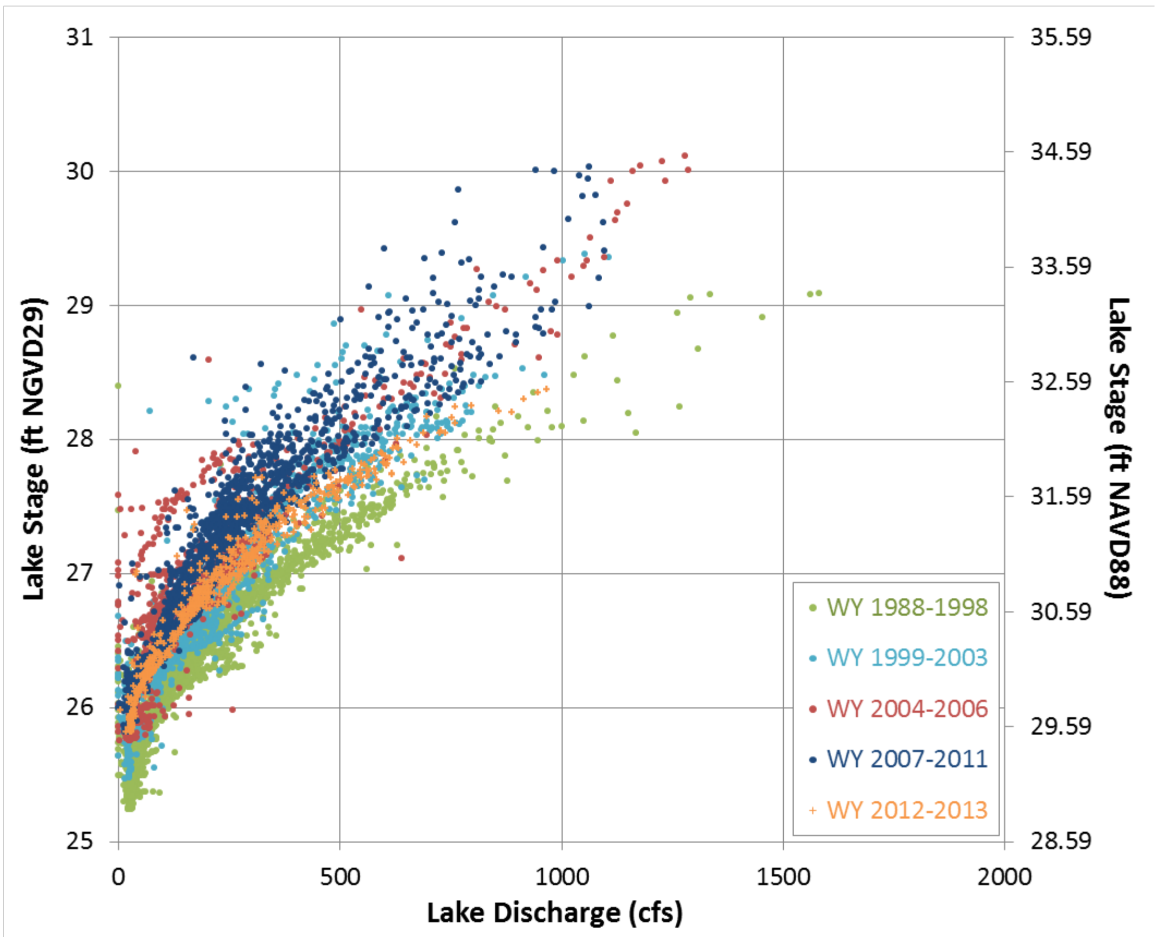


Figure 11. Relationship between lake discharge and lake elevation for five sub-periods of record. Lake discharge was estimated indirectly, on the basis of streamflow records for Sammamish River and Bear Creek.

Readily apparent from Figure 11 is the presence of multiple shifts over time in the lake elevation-discharge relationship. The plot shows a clear upward shift in elevation-discharge after 1998, meaning that the lake level associated with a particular discharge increased. The weir modifications, which included raising the weir level across most of the weir section (see Section 2.1), are consistent with such an impact. There seems to be more scatter in the post-1998 data, but the period from 2004 to 2006 is generally the highest while the last two years are the lowest since the weir was modified. These periods correspond to, respectively, very limited TZ vegetation maintenance (2004 to 2006) and intensive annual mowing (2012 to 2013), supporting the idea that TZ vegetation has a measurable impact on lake discharges.

It is also well-recognized (e.g., King County, 2012a) that backwater effects from high Bear Creek discharge can diminish the lake's discharge capacity for a given stage, creating an impairment in the lake's weir rating curve during large events. During events with high Bear Creek flows, Bear Creek inflows raise the water surface in the channel downstream of the TZ, which in turn raises the water surface through the TZ and even back to the weir. This reduces discharge capacity over the weir (which depends on the difference in water surface elevation over the weir), and if lake inflows exceed discharge capacity, the lake continues to fill. As Bear Creek flows recede, water levels downstream of the weir decrease, increasing discharge capacity. Thus as the lake peaks and begins to subside, the discharge as lake level decreases is higher than it was on the rising limb (i.e., as lake level went up) for the equivalent lake level. This effect, referred to as a hysteresis, is illustrated in Figure 12.

It is informative to contrast lake discharge capacity during two of the largest events in the record: the event of January 1-9, 1997, during which the highest ever lake levels were recorded, and the event of February 8-12, 1996, which ranked fifth with regard to lake elevation. The daily elevation and discharge values during these two events are shown in Figure 12, showing the hysteresis loop habitually seen in large events (King County, 2012a). While the two events have the same starting and end points in Figure 12, they take disparate courses in between.

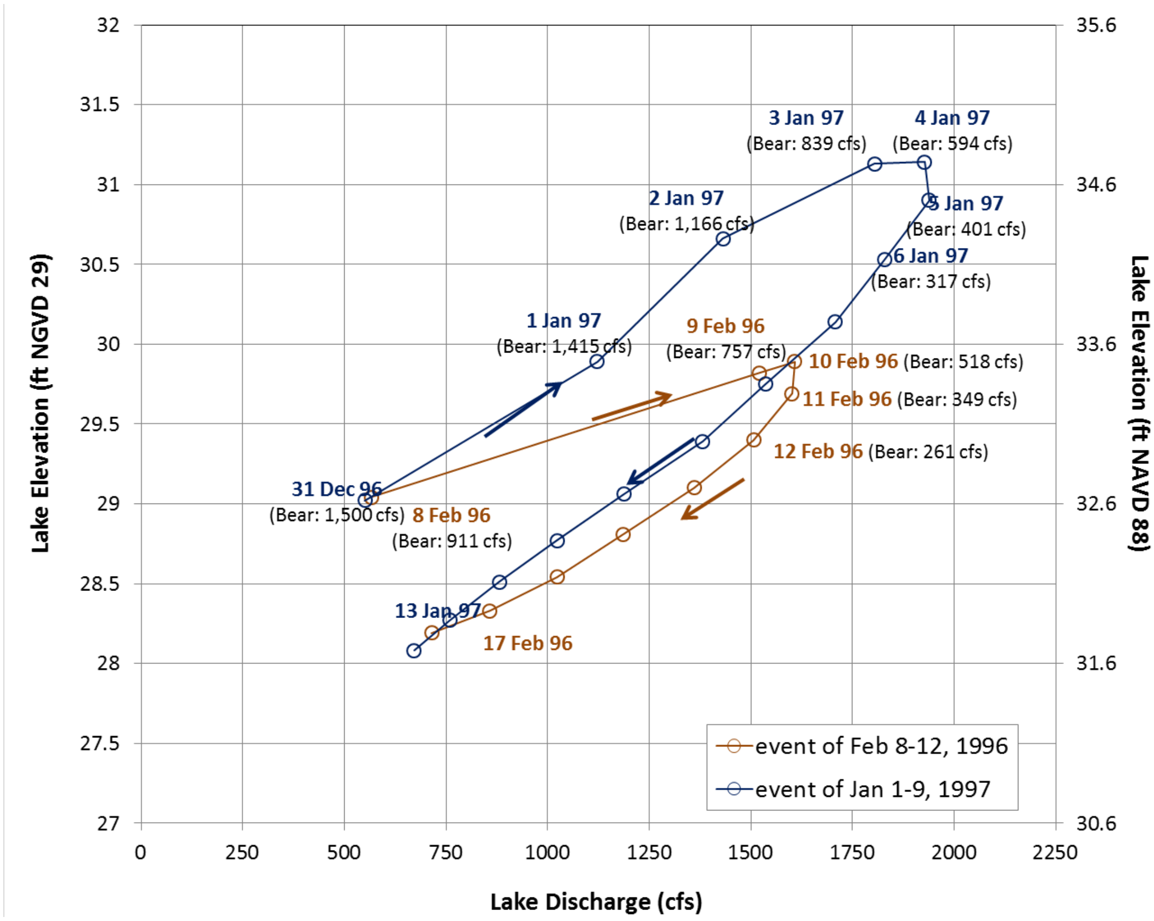


Figure 12. Elevation-discharge comparison for two extreme events. The February 1996 event achieves higher discharge for similar elevations compared to the January 1997 event.

For each date label in Figure 12, the mean daily discharge recorded at Bear Creek is also provided. The much higher Bear Creek discharge values during the January 1997 event compared to February 1996 are the likely explanation for the higher lake elevations in the 1997 event for comparable outflows. Both events occurred under similar TZ vegetation conditions and prior to the 1998 weir modification. The January 1997 event, which gave rise to the highest estimated lake discharge in the period of record, saw exceptional discharges coming from Bear Creek. Only after January 2 did the daily discharge from Bear Creek drop below the discharge from the lake itself.

3.4 Summary of Results

Data analyses conducted for this study point to significant changes in hydrologic conditions through the lake and TZ since construction of the Sammamish River flood control project in 1964. Annual peak flows on the Sammamish River downstream of Bear Creek have increased considerably. The 10-year annual flow, which the Corps equated to the 1,500 cfs design flow, is roughly 2,000 cfs based on streamflow data since 1965. Although Bear Creek flows have also likely increased somewhat, the downstream increase is probably mostly attributable to the project itself.

Inflows to Lake Sammamish, as represented by Issaquah Creek, have shown no significant increases, but late summer low flows have decreased significantly. This led to a corresponding decrease in summer lake levels until the outlet weir was modified in 1998. The weir modifications are consistent with an observed post-1998 upward shift in minimum lake levels, and there has been a coincident increase in moderate lake levels as well. The duration of lake levels exceeding 27 feet NGVD (30.6 feet NAVD) since 1998 is about 50 percent higher than the long-term average, and statistical tests indicate that post-1998 lake levels are distinctly different from pre-1998 levels. This may account for the higher OHW level determined in a 2004 study (roughly 28 feet NGVD compared to the accepted 27 feet NGVD level). It is not clear whether impacts extend to peak lake levels.

The highest lake levels on Lake Sammamish are concentrated in the past 25 years, with nearly 90 percent occurring since 1990. Based on examination of the data, a number of factors have been identified as contributing to extreme lake levels, including:

- High or prolonged inflows to Lake Sammamish
- High antecedent lake levels (i.e. lake levels prior to a storm event)
- Vegetation condition in the TZ
- Backwater from high Bear Creek flows

Examination of discharges determined independently from the weir rating curve (direct measurements and computed estimates) clearly indicates a dynamic elevation-discharge relationship at the weir. The relationship varies both within large events, primarily due to backwater effects from high Bear Creek flows, and over periods of months to years, apparently reflecting changes in vegetation (i.e. hydraulic roughness) in the TZ.

4 Design Considerations for Future Hydrology

Past experience and current scientific evidence suggest that there is a potential for systematic hydrologic changes—notably increases in peak flows and storm volumes—over the life of the Willowmoor project due to land use and/or climate change. To assure a robust design under future conditions, the County would like to identify and account for realistic future hydrologic conditions in the design hydrology.

4.1 Land Use Change

Based on rates and type of development in the Lake Sammamish and Bear Creek basins, we know that streamflows have been affected by land use change since the original project construction. Since few of the available gage records extend back before the late 1980s, a hydrologic modeling analysis would likely be needed to estimate the extent of that change and its effects on lake levels. While it would be interesting to quantify the land use impacts to date, it is probably not particularly important to establishing design hydrologic conditions for the Willowmoor project.

In terms of land use, current conditions are likely to be critical in terms of peak flows and storm volumes. Remaining undeveloped portions of the watershed, primarily in the Issaquah and Bear/Evans Creek basins, are outside of designated urban growth areas and would not expect to see significant development over the life of the project. Furthermore, under current Washington State stormwater management standards, redevelopment and new development require flow control mitigation to essentially match forested condition flows for most significant storm events. In the case of redevelopment of existing impervious surfaces, the required mitigation would actually reduce peak flows, as well as volumes through the peak of the hydrograph. For these reasons, *significant* flow increases due to further land use change are judged to be unlikely.

4.2 Climate Change

The following sections explore the types of storms that have historically produced large events in the Sammamish watershed and how current research suggests these may change as a result of projected climate change. These results suggest how we might use such projections to develop realistic estimates of frequency and intensity of future extreme events in the Sammamish basin.

4.2.1 Atmospheric Circulation Patterns Associated with Extreme Streamflows

Atmospheric rivers (ARs) are long (greater than 2,000 km) and narrow (less than 1,000 km) plumes of water vapor in the lower troposphere (e.g., Bao et al., 2006; Ralph et al., 2004) that are associated with extreme precipitation intensity and volume. ARs are associated with many significant flooding events in western Washington (e.g., Neiman et al., 2011) and throughout the North American west coast, where they produce roughly twice as much precipitation as non-AR storms (Neiman et al., 2008). Their impact on California hydrologic extremes has been most widely studied (e.g., Dettinger, 2004; Ralph et al., 2006).

Table 9 shows the hydrographs and satellite imagery of atmospheric water vapor (vertically-integrated water vapor, or IWV) observed on the dates of the highest streamflows in the Issaquah Creek record and establishes the connection between extreme flows and landfall of ARs seen on each of the images. The event of December 3, 1975, which ranked second for daily streamflow, predates available satellite imagery. Its hydrograph is shown in Table 8. Even in the absence of imagery, it is nevertheless clear that this extreme event was very large in spatial scale, affecting vast areas of western Washington, and was particularly devastating in Snohomish County[9]. For the case of November 24, 1986, the satellite image for the preceding date is also shown in Table 9, and the magnitude of the downpour that occurred in the interim 24 hours can be judged by comparing the two images.

In their analysis of flooding in four watersheds from different western Washington locations (the Queets, Satsop, Sauk, and Green watersheds), Neiman et al (2011) noted that the Green River has the most marked inter-annual variability, with its peak annual daily streamflows varying by an order of magnitude from year to year. Issaquah Creek, the main tributary of Lake Sammamish, neighbors the Green River at slightly lower elevation, and its inter-annual variability is also marked. Neiman et al (2011) attributed this wide variability to the fact that only a small subset of ARs reach the Green River basin, namely those that enter from the narrow window between the Olympic Mountains and Mount Rainier. Given the proximity of the Lake Sammamish watershed to the Green River basin, and the former's lower altitude, it appears likely that this same phenomenon, which selects for a subset of ARs, explains the high inter-annual variability of peak annual streamflow in Issaquah Creek, Bear Creek, and the Sammamish River, and, by implication, a high inter-annual variability of peak lake levels. The images in Table 9 are all within this narrow window of AR directions.

From their analysis of the four watersheds' streamflow records, Neiman et al (2011) concluded that landfalling ARs were responsible for nearly all annual peak daily streamflows in western Washington (the exceptions being events of rapid snowmelt, a factor largely absent in the case of Issaquah Creek, given its low elevation) during the 30 water years studied (1980-2009). They found the same to be true for all peak daily flows exceeding the five-year return period.

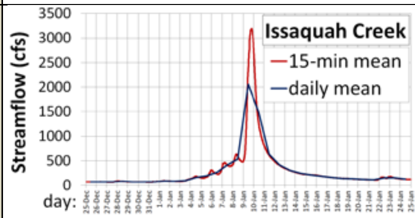
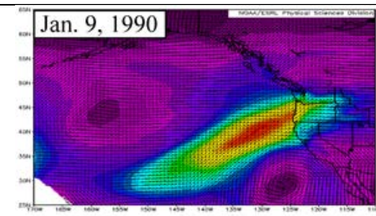
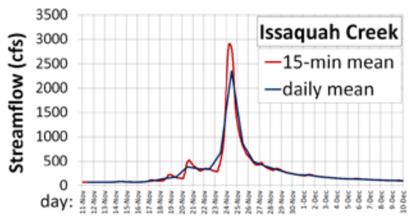
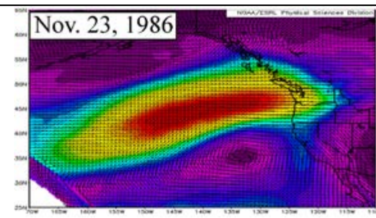
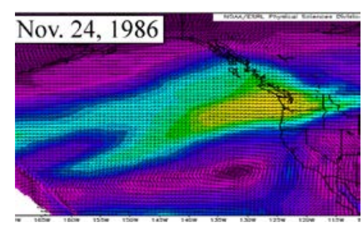
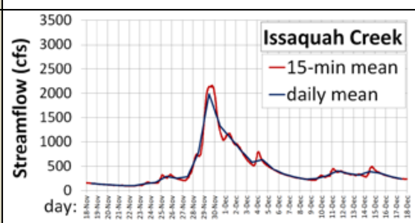
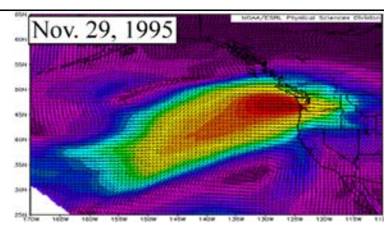
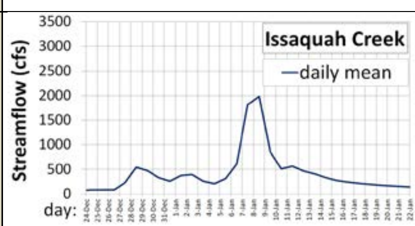
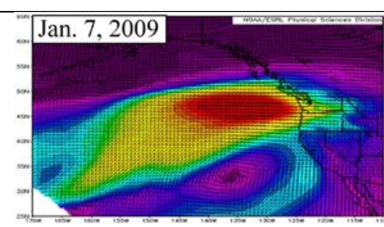
Neiman et al. (2011) concluded as follows:

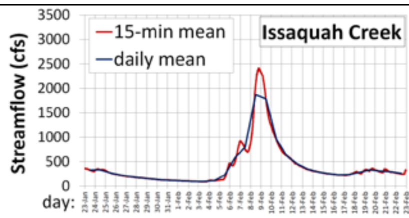
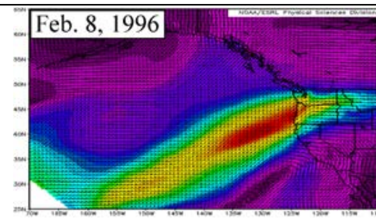
> Those ARs that produced flooding typically exhibited two or more of the following attributes:

[9] http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=8504

(i) the AR was optimally oriented for orographic precipitation enhancement in a given basin,
(ii) the low-level onshore water vapor fluxes into the basin were quite strong,
(iii) the AR stalled over the basin,
(iv) the melting level was especially high, and/or
(v) basin soils were already saturated prior to AR landfall.

Table 9. Hydrographs and atmospheric vapor transport for extreme events. For second ranked event (3 December 1975), which precedes satellite imagery, see Table 8. Satellite imagery from Neiman et al. (2011, suppl. mat.).

Rank	Date	Issaquah Creek Hydrograph	Atmos. Integrated Vapor Transport (km s^{-1} m^{-1}) 
1	**Jan. 9, 1990**		
3	**Nov. 24, 1986**		 
4	**Nov. 29, 1995**		
5	**Jan.7-8, 2009**		

<table>
<tr><th>Rank</th><th>Date</th><th>Issaquah Creek Hydrograph</th><th>Atmos. Integrated Vapor Transport (km s^{-1} m^{-1})
</th></tr>
<tr><td>6</td><td>Feb.8-9, 1996</td><td></td><td></td></tr>
</table>

These results demonstrate that the largest recorded streamflow events in Issaquah Creek, the principal tributary to Lake Sammamish, have been associated with the landfall of atmospheric rivers, and are therefore explained by large-scale atmospheric circulation patterns over the Northern Pacific Ocean, as they interact with the regional and local topography.

4.2.2 Future Projections and Suggested Approach

The location of the North Pacific low-pressure center known as the Aleutian Low, which fluctuates from year to year, has been shown to determine the path of the storm track (e.g., Hartmann and Wendler, 2005). Simulations by several global climate models (GCMs) are capable of adequately reproducing the North Pacific storm track that brings ARs and intense storms to western Washington and elsewhere on North America's Pacific coast (e.g., Yin, 2005). GCM simulations for future periods show that associated with global warming is an increase in the frequency with which the Aleutian Low takes more northerly positions and an intensification of its low pressure strength (Yin, 2005; Kushner et al., 2001). As a result, the North Pacific storm track moves northward, favoring more frequent and intense storms in the Pacific Northwest. Downscaled GCM results indicate that precipitation in western Washington will be more intense not only due to the increased frequency of large-scale storms entering the coast, but also due to changes in the intensity of these storms as they interact with the region's topography, phenomena that are simulated by regional climate models and statistical downscaling (Salathé, 2006). Some of these and other published results were reviewed in the King County (2010) document.

For purposes of project design, the future hydrology should reflect a realistic representation of the increased frequency and intensity of these AR events that cause extreme streamflows in the Sammamish River basin. The frequency with which ARs (including those approaching from directions effective at producing high streamflows in the Lake Sammamish watershed) are projected to make landfall in this region can be directly derived from multiple GCM results, without prior downscaling. Alternatively, Dulière et al (2011) showed that fine-resolution regional climate model (RCM) simulations (12-km grid spacing), used to downscale from GCM projections, are capable of adequately representing precipitation extremes. The availability of simulations of future climate downscaled to such fine scale is very limited, however (see Salathé et al., 2010), so direct analysis of GCM results is the preferred approach.

At the scale of the Sammamish River basin, even RCM simulations are unlikely to reliably represent precipitation intensities. Given the projected intensification of ARs, and the prospect of extreme high-intensity and long-lasting precipitation that can result from an AR moving slowly or stalling over a region (see e.g., Ralph et al., 2011), we can expect that runoff generated in extreme events is likely to increase. As a fairly simple way to represent this effect, large events from the historical record could be concatenated to represent a particularly severe storm with quite realistic possibility of occurring. This approach is similar to the one suggested as the basis for an emergency preparedness scenario for California, by Dettinger et al. (2012).

Precipitation records used as input to the hydrologic models can be modified, replacing the largest historical storm events with the composite storms. The number of composite storms in the precipitation record would be based on the estimated frequency of AR events (compared to the historic record) to produce what we estimate to be a realistic frequency distribution of more typical and severe storms. The resulting composite climatology can then be used to drive our hydrologic and hydraulic models to evaluate streamflows and lake elevations for project alternatives under potential future conditions.

5 Conclusions and Recommendations

One of the key findings of this study is the confirmation of the impact of the TZ and Bear Creek on peak lake levels. Reduced lake outflows can be clearly linked to vegetation conditions in the TZ and high outflow from Bear Creek, and appear to have contributed to some of the highest observed lake levels. Both of these factors have been previously recognized but need to be explicitly and collectively considered in design of modifications to the TZ.

This study also demonstrated significant changes in low to moderate lake levels, up to at least the OHW level. Exceedances and durations above the 27- to 28-foot NGVD levels (30.6 feet to 31.6 feet NAVD) have increased significantly in the past 15 years compared to prior levels, and it seems likely that these changes result from the weir modifications in 1998. Statistical analyses indicate that increasing occurrences of high lake levels are not accompanied by corresponding inflow or precipitation trends (which would suggest a climatic origin).

Based on the review and analyses conducted in this work and other recent studies (e.g. King County, 2012a), we conclude that several of the hydrologic assumptions used by the Corps of Engineers for the design of the Sammamish River Flood Control project in the mid-1960s are outdated. Using updated records and analysis, the 1,500 cfs project design flow is now substantially less than the 40-year spring flow/10-year annual flow to which it was equated in the design documents. Even with higher flows, the project continues to meet its primary objective of eliminating spring flooding while keeping lake levels below 29 feet NGVD (32.6 feet NAVD). The Willowmoor project design should also consider whether spring flooding remains the most critical flood protection scenario, with development of much of the downstream agricultural area.

Recommended next steps for determining design hydrology for the Willowmoor project include:

1. Definition of goals and constraints. These include determination of desired level of downstream flood protection, target lake level(s) and exceedance frequencies, and potential seasonal target flows and duration (e.g. to meet fish and recreation needs), as well as definition of a realistic vegetation management scenario or scenarios. It may be useful to consider minimum project targets (i.e. equivalent to existing) and “optimal” project targets (e.g. enhanced lake level protection).
2. HSPF model updates. This would include updating the Issaquah Creek, Bear/Evans Creek, Lake Sammamish tributaries, and Sammamish River models to current land use[10] (if necessary) and recalibrating the Issaquah Creek and Bear/Evans Creek models to available gage data. General calibration adjustments common to both models would also be applied to the uncalibrated

[10] Snohomish County models (Swamp, North, and Little Bear Creeks) have been more recently updated and calibrated than King County models and are less critical to analysis of the TZ.

models, as appropriate.

3. HEC-RAS model refinement focusing on the reach between Bear Creek and Lake Sammamish. This would include a period-of-record simulation using the existing HEC-RAS model with updated hydrologic inputs and comparison to appropriate observed data. Calibration of TZ vegetation conditions for the top lake level events could also be included.
4. Future conditions analysis. This could include climate analysis and development of future conditions precipitation records (as discussed in Section 4.2) and HSPF simulations (for all tributary models) with the modified precipitation inputs. Flow outputs would then be used as input for a period-of record HEC-RAS simulation to determine downstream (Lake Sammamish and Sammamish River) conditions under future hydrology. In lieu of this detailed analysis, a targeted sensitivity analysis could be used to encompass a range of uncertainties.
5. Selection of design events. Design events appropriate to the project targets would be selected from both the existing and future conditions modeling. Because of the time-varying influence of Bear Creek on the lake outlet, unsteady hydraulic model simulations will be important for project design. Thoughtful selection of design events and initial conditions from the continuous hydrologic modeling should obviate the need for extended hydraulic simulations to evaluate design concepts, however.

Going forward, it seems likely that revised design hydrology and flood protection objectives can be developed that will maintain at least an equivalent level of protection to the project's original objectives while reflecting changes in flood management priorities and project maintenance constraints and incorporating evolving management goals, such as habitat enhancement, recreational use, and lake level regulation.

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Appendix A – Trend Analysis Results

1 Homogeneity tests for lake stage time series

Here we apply three classical homogeneity tests to each of the following annual time series:

- The **minimum** daily value in each water year
- The **10th percentile** of daily values in each water year
- The **25th percentile** of daily values in each water year
- The **50th percentile** (median) of daily values in each water year
- The **mean** of the daily values in each water year
- The **90th percentile** of daily values in each water year
- The **maximum** daily value in each water year

1.1 Standard Normal Homogeneity Test

This test was introduced by Alexandersson (1986).

Consider n years i and the corresponding annual values y_i. The mean and standard deviation of the n annual values y_i are $\bar{y}$ and s, respectively.

We compare the means of the normalized values for the first k years with those of the rest of the years, from k+1 to n. We do this multiple times, for all values of k, from k =1 through k =n-1.

The mean of the normalized values in the set of the first k years, and in the set of the remainder n -1 years is

$$\bar{z}_1 = \frac{1}{k} \cdot \sum_{i=1}^{k} \frac{(y_i - \bar{y})}{s} \;\; and \;\; \bar{z}_2 = \frac{1}{n-k} \cdot \sum_{i=k+1}^{n} \frac{(y_i - \bar{y})}{s} \qquad , k = 1, \ldots, n-1 \qquad \textbf{Eq. 1}$$

The test statistic is $T(k)$, defined as

$$T(k) = k \cdot \bar{z}_1^2 + (n-k) \cdot \bar{z}_2^2 \qquad , k = 1, \ldots, n-1 \qquad \textbf{Eq. 2}$$

The maximum value of $T(k)$ over all k is T_0:

$$T_0 = max_{1 \le k \le n-1} T(k)$$

Eq. 3

The series is inhomogeneous at year k if T_0 is above a critical value, which depends on sample size. Table A-1 reproduced from Khaliq and Ouarda (2007), provide critical values.

Table A-1. Critical values for statistic T_0, from Khaliq and Ouarda (2007).

CRITICAL VALUES OF THE SNHT 685

Table I. Critical values of the SNHT statistic T for various sample sizes and corresponding to six selected critical levels.

Sample size	Critical level (%)						Sample size	Critical level (%)					
	90	92	94	95	97.5	99		90	92	94	95	97.5	99
10	4.964	5.197	5.473	5.637	6.188	6.769	145	8.063	8.529	9.120	9.490	10.877	12.660
12	5.288	5.554	5.876	6.068	6.729	7.459	150	8.086	8.554	9.147	9.519	10.906	12.694
14	5.540	5.831	6.187	6.402	7.152	8.001	155	8.111	8.578	9.172	9.543	10.933	12.725
16	5.749	6.059	6.441	6.674	7.492	8.440	160	8.133	8.601	9.195	9.569	10.966	12.759
18	5.922	6.248	6.652	6.899	7.775	8.807	165	8.155	8.625	9.222	9.596	10.992	12.793
20	6.070	6.410	6.830	7.089	8.013	9.113	170	8.174	8.643	9.241	9.615	11.016	12.820
22	6.200	6.551	6.988	7.257	8.220	9.380	175	8.195	8.666	9.265	9.641	11.046	12.851
24	6.315	6.675	7.123	7.400	8.400	9.609	180	8.214	8.685	9.283	9.658	11.062	12.872
26	6.417	6.785	7.246	7.529	8.558	9.812	185	8.233	8.706	9.307	9.683	11.089	12.904
28	6.509	6.884	7.353	7.643	8.697	9.993	190	8.252	8.725	9.325	9.701	11.110	12.930
30	6.592	6.973	7.451	7.747	8.825	10.153	195	8.268	8.741	9.343	9.720	11.132	12.956
32	6.669	7.056	7.541	7.841	8.941	10.300	200	8.286	8.761	9.364	9.741	11.156	12.982
34	6.741	7.132	7.625	7.930	9.050	10.434	225	8.361	8.838	9.446	9.826	11.247	13.083
36	6.803	7.201	7.699	8.009	9.143	10.552	250	8.429	8.908	9.516	9.898	11.329	13.175
38	6.864	7.263	7.768	8.081	9.230	10.663	275	8.489	8.970	9.581	9.966	11.399	13.248
40	6.921	7.324	7.835	8.151	9.317	10.771	300	8.540	9.022	9.635	10.020	11.460	13.326
42	6.972	7.380	7.894	8.214	9.390	10.865	325	8.587	9.070	9.685	10.071	11.517	13.389
44	7.022	7.433	7.951	8.273	9.463	10.957	350	8.633	9.117	9.732	10.118	11.565	13.440
46	7.071	7.484	8.007	8.331	9.530	11.040	375	8.670	9.157	9.775	10.161	11.613	13.494
48	7.112	7.529	8.054	8.382	9.592	11.116	400	8.706	9.193	9.814	10.202	11.654	13.542
50	7.154	7.573	8.103	8.432	9.653	11.193	425	8.738	9.224	9.844	10.234	11.692	13.580
52	7.194	7.616	8.149	8.480	9.711	11.259	450	8.771	9.260	9.882	10.272	11.730	13.623
54	7.229	7.654	8.190	8.524	9.760	11.324	475	8.798	9.288	9.912	10.302	11.761	13.655
56	7.264	7.690	8.230	8.566	9.810	11.382	500	8.828	9.317	9.939	10.330	11.795	13.690
58	7.299	7.727	8.268	8.606	9.859	11.446	525	8.854	9.344	9.967	10.360	11.827	13.730
60	7.333	7.764	8.308	8.647	9.906	11.498	550	8.878	9.369	9.995	10.386	11.854	13.751
62	7.363	7.796	8.343	8.683	9.947	11.548	575	8.901	9.391	10.016	10.408	11.878	13.782
64	7.392	7.827	8.375	8.717	9.985	11.599	600	8.923	9.414	10.040	10.431	11.904	13.813
66	7.421	7.857	8.408	8.752	10.026	11.648	650	8.963	9.455	10.083	10.476	11.949	13.856
68	7.449	7.886	8.439	8.784	10.067	11.692	700	9.001	9.493	10.119	10.511	11.986	13.904
70	7.475	7.913	8.467	8.814	10.099	11.737	750	9.033	9.524	10.152	10.547	12.026	13.947
72	7.499	7.938	8.496	8.844	10.134	11.776	800	9.063	9.557	10.187	10.580	12.059	13.975
74	7.525	7.965	8.523	8.873	10.171	11.822	850	9.093	9.587	10.216	10.612	12.096	14.023
76	7.547	7.989	8.548	8.898	10.200	11.858	900	9.119	9.614	10.244	10.640	12.120	14.041
78	7.570	8.013	8.575	8.926	10.230	11.895	950	9.143	9.638	10.269	10.665	12.149	14.070
80	7.591	8.035	8.599	8.951	10.259	11.928	1000	9.168	9.664	10.295	10.692	12.176	14.105
82	7.613	8.059	8.623	8.976	10.290	11.966	1100	9.211	9.708	10.339	10.736	12.220	14.150
84	7.634	8.079	8.647	9.001	10.315	11.995	1200	9.246	9.745	10.377	10.775	12.263	14.197
86	7.655	8.102	8.670	9.026	10.347	12.033	1300	9.283	9.781	10.415	10.812	12.304	14.235
88	7.673	8.121	8.691	9.047	10.370	12.059	1400	9.313	9.812	10.446	10.845	12.340	14.271
90	7.692	8.140	8.710	9.067	10.394	12.089	1500	9.347	9.846	10.481	10.880	12.374	14.312
92	7.711	8.160	8.732	9.090	10.417	12.120	1600	9.372	9.871	10.506	10.904	12.396	14.339
94	7.730	8.181	8.752	9.110	10.447	12.153	2000	9.464	9.965	10.603	11.002	12.500	14.443
96	7.745	8.196	8.770	9.127	10.465	12.175	2500	9.551	10.052	10.690	11.089	12.591	14.540
98	7.762	8.214	8.788	9.147	10.484	12.196	3000	9.618	10.121	10.760	11.161	12.664	14.619
100	7.778	8.231	8.807	9.167	10.507	12.228	3500	9.675	10.178	10.818	11.219	12.727	14.683
105	7.819	8.273	8.851	9.214	10.562	12.291	4000	9.727	10.229	10.869	11.271	12.779	14.734
110	7.856	8.312	8.892	9.255	10.608	12.343	4500	9.766	10.269	10.911	11.313	12.820	14.777
115	7.891	8.350	8.931	9.296	10.656	12.401	5000	9.803	10.307	10.948	11.349	12.859	14.817
120	7.921	8.380	8.963	9.330	10.694	12.446	7500	9.938	10.442	11.085	11.487	12.997	14.959
125	7.952	8.413	8.999	9.365	10.735	12.488	10 000	10.031	10.537	11.180	11.584	13.095	15.063
130	7.983	8.446	9.032	9.400	10.772	12.538	15 000	10.152	10.658	11.302	11.707	13.221	15.186
135	8.010	8.474	9.063	9.431	10.808	12.579	20 000	10.236	10.743	11.388	11.791	13.305	15.271
140	8.038	8.501	9.092	9.462	10.845	12.621	50 000	10.480	10.988	11.634	12.039	13.556	15.523

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Results

Our sample size (water years 1965-2012) is n=48. The values in Table A-1 are 7.112 and 8.382 for test significance of 10% (90% confidence level) and 5% (95% confidence level), respectively. We therefore conclude on the basis of this test, at the 90% certainty level, that all of these time series are inhomogeneous, excepting the minimum and maximum time series. The most likely break point is centered roughly about 1995 in most cases, and 1996 in the case of the 10th percentile series.

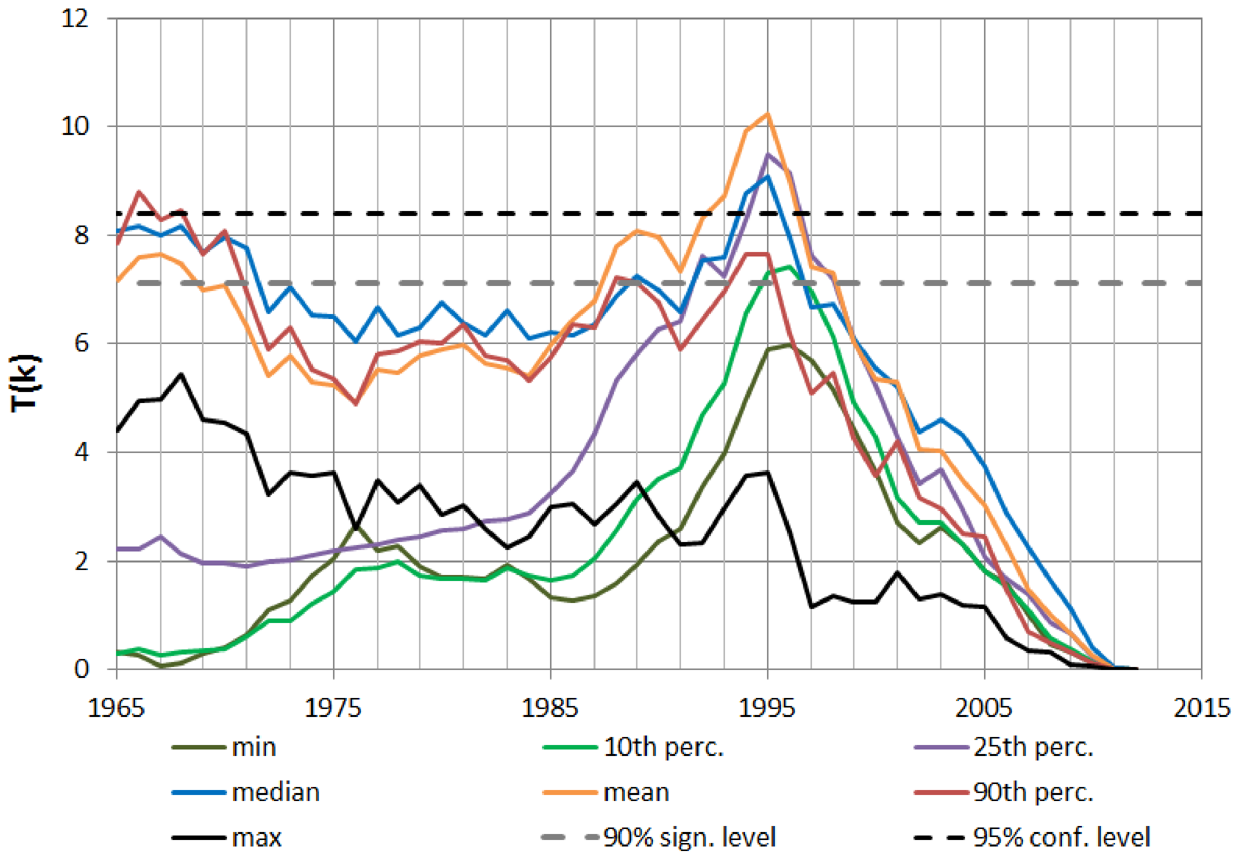


Figure A-1. Values of the T_0 statistic for the Standard Normal Homogeneity Test

1.2 Buishand Range Test

This test was introduced by Buishand (1982).

Consider n years i and the corresponding annual values y_i. The mean and standard deviation of the n annual values y_i are $\bar{y}$ and s, respectively. The adjusted partial sum over the series formed by the first k years, S_k* is

$$S_k^* = \sum_{i=1}^{k}(y_i - \bar{y}) \quad , \quad k = 1, \ldots, n-1 \qquad \textbf{Eq. 4}$$

The range covered by Sk* over all k, divided by the standard deviation of the complete series of n years (s) is designated the rescaled adjusted range, R.

$$R = \frac{1}{s} \cdot (\max_{1 \le k \le n-1} S_k^* - \min_{1 \le k \le n-1} S_k^*) \qquad \textbf{Eq. 5}$$

The test statistic is given by T_0:

$$T_0 = \frac{R}{\sqrt{n}} \qquad \textbf{Eq. 6}$$

The series is inhomogeneous at year k if T_0 is above a critical value, which depends on sample size, according to Table A-2 (reproduced from Winjgaard *et al.*, 2003).

Table A-2. Critical values of statistic T_0 for sample size n and two statistical significance levels.

n	20	30	40	50	70	100
1%	1.60	1.70	1.74	1.78	1.81	1.86
5%	1.43	1.50	1.53	1.55	1.59	1.62

Results

The values in Table A-2 follow an approximately linear relationship between n=40 and n=70, and we used linear interpolation between n=40 and n=50 to obtain for n=48 the value 1.55 for the 5% significance level and 1.77 for the 1% significance level. Values of test statistic T_0 are shown in Figure A-2 for all values of *k* (indicated by the corresponding year). The most likely break point is centered around 1997 or 1996, depending on the series.

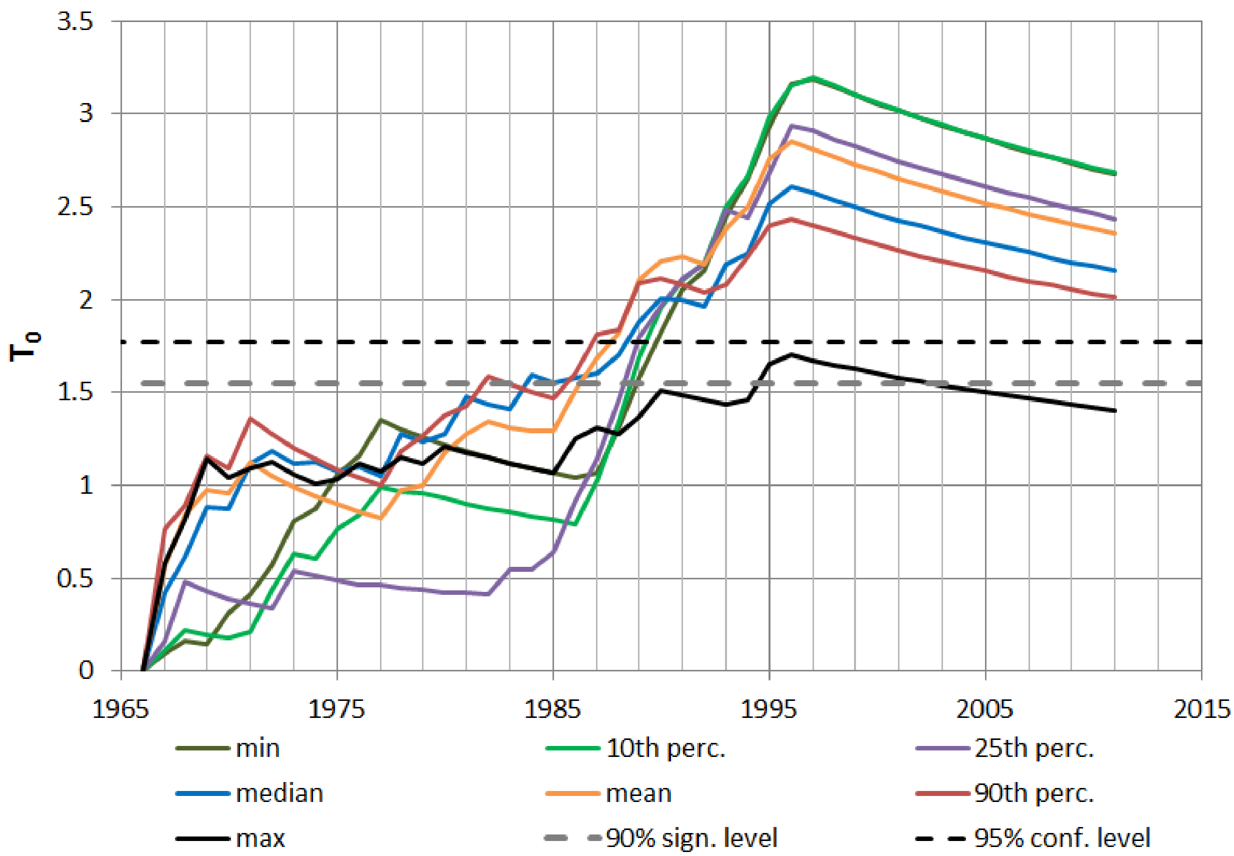


Figure A-2. Values of test statistic T_0 for our time series.

1.3 Pettitt Rank Test

This test was introduced by Pettitt (1979).

This is a non-parametric rank test. The annual values $y_i, \ldots, y_n$ and their respective ranks $r_i, \ldots, r_n$ are used to calculate the statistics X_k:

$$X_k = 2 \cdot \sum_{i=1}^{k} r_i - k \cdot (n+1) \quad , \qquad k = 1, \ldots, n-1 \qquad \textbf{Eq. 7}$$

The test statistic X_E is defined as

$$X_E = \max_{1 \le k \le n-1} |X_k| \qquad \textbf{Eq. 8}$$

The series is inhomogeneous at year k if X_E is above a critical value, which depends on sample size, according to Table A-3 (reproduced from Winjgaard *et al.*, 2003).

Table A-3. Critical values of statistic X_E for sample size n and two statistical significance levels.

n	20	30	40	50	70	100
1%	71	133	208	293	488	841
5%	57	107	167	235	393	677

Results

The values in Table 3 follow an approximately linear relationship between n=40 and n=70, and we used linear interpolation between n=40 and n=50 to obtain the values 221.4 and 276 for the 5% and 1% confidence levels, respectively. Values of test statistic *X(k)* are shown in Figure A-3 for all values of k (indicated by the corresponding year), for each of our series. On the basis of this test, the most likely breakpoint is centered about 1995.

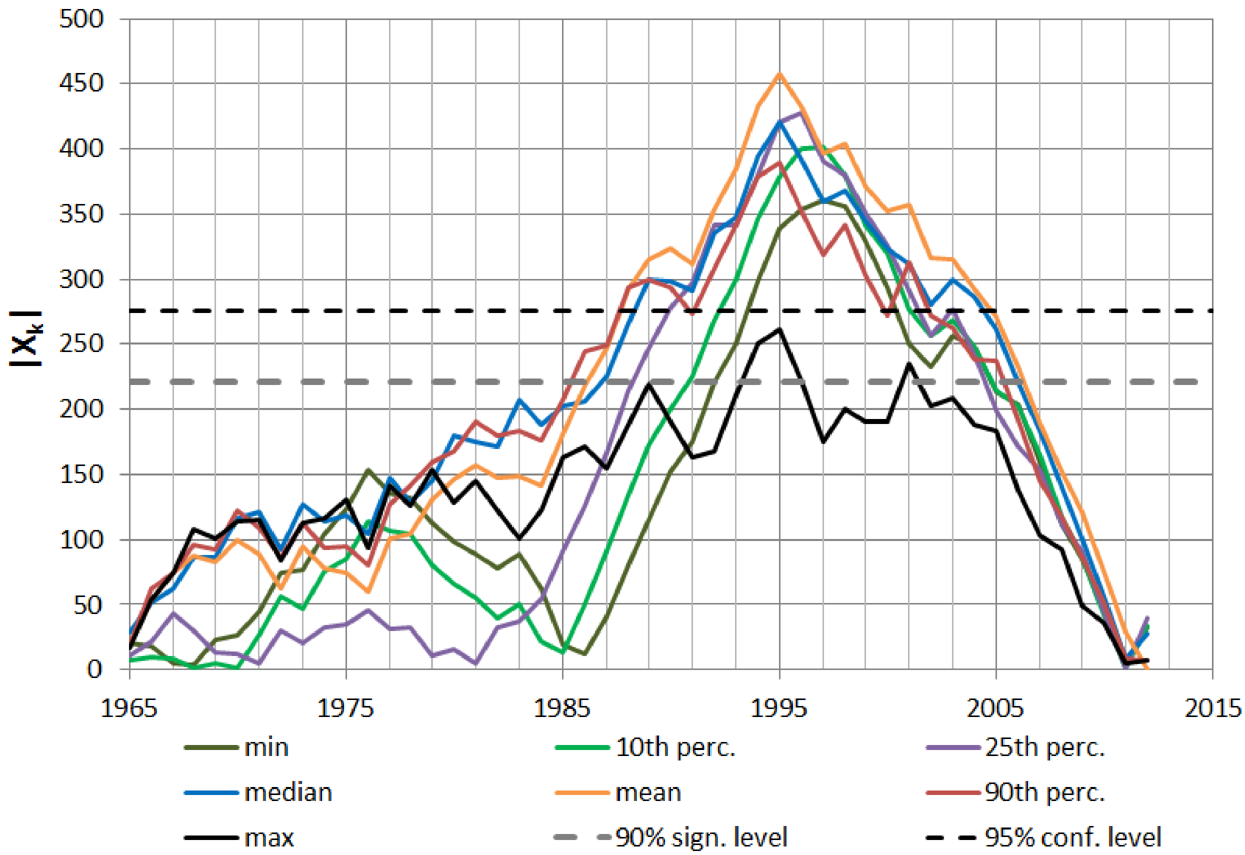


Figure A-3. Values of test statistic $|X_k|$ for our time series.

1.4 Effect of Shifting Water Years 1996-1997

We suspect that test statistics peak prior to modifications to the Lake Sammamish outlet weir in 1998 because of the presence of two prior wet years (water years 1996 and 1997) immediately preceding the weir modifications that appear to have generally increased lake levels. Here we apply the same homogeneity tests with water years 1996-1997 relocated in the lake level record to 1980-1981. The sequence of 1980-1995 was shifted forward two years, so the same data are still present but water years reordered. Results of the tests on the modified time series are shown in Figures A-4 through A-6. As expected, the most likely breakpoint shifts to 1997/1998, though significance of the results is affected in some cases.

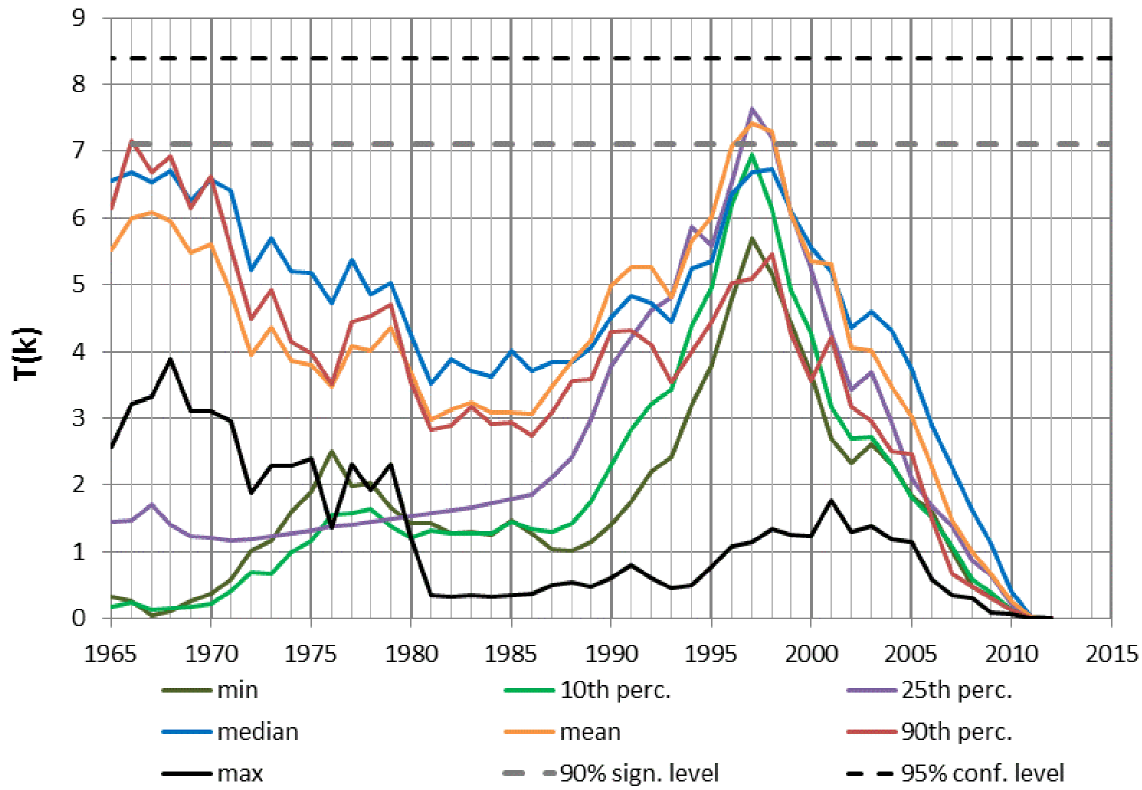


Figure A-4. Values of the Standard Normal test statistic for modified time series.

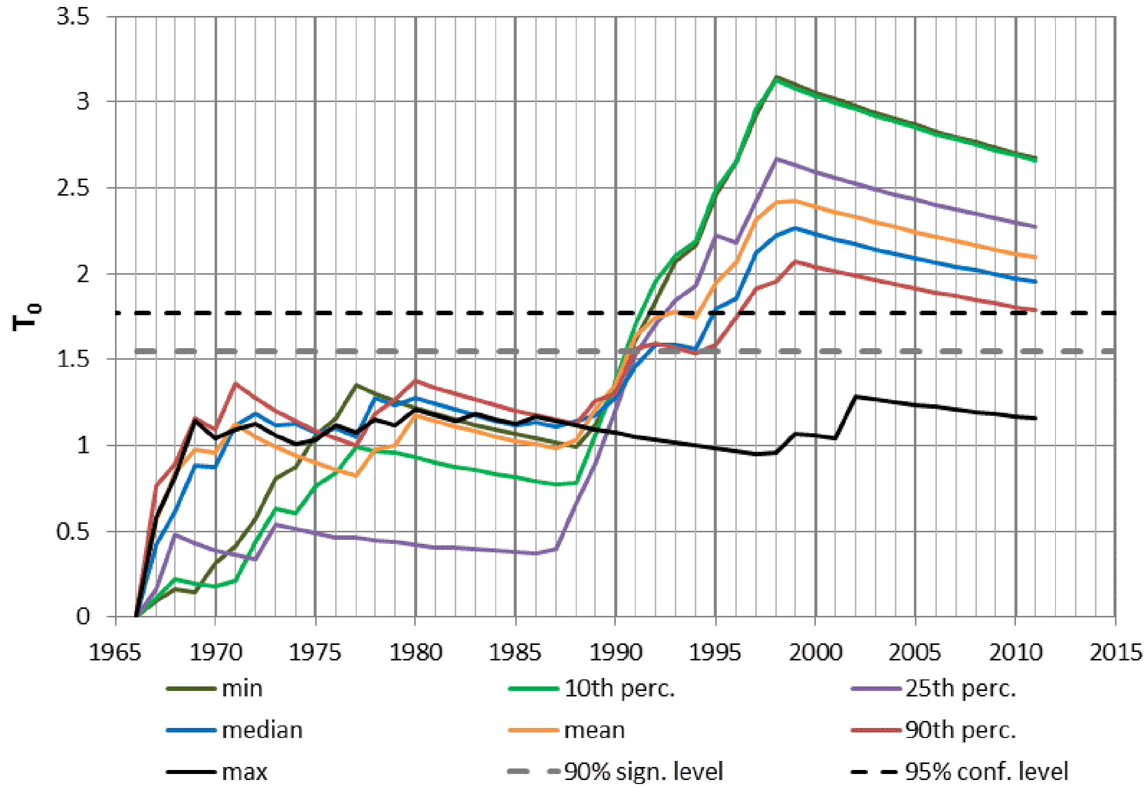


Figure A-5. Values of the Buishland Range test statistic for modified time series.

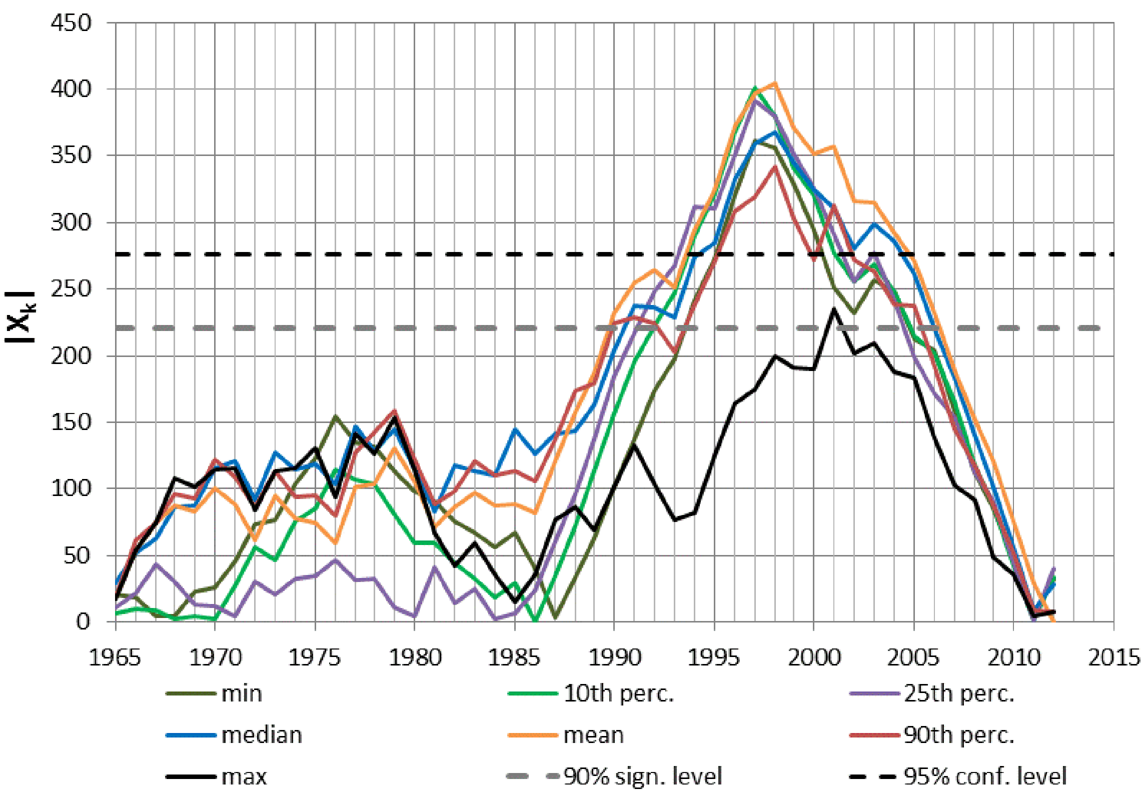


Figure A-6. Values of the Pettitt Rank test statistic for modified time series.

2 Study of trends in the period 1965-1997

In 1998, a notch was introduced to the weir to enhance low flows and facilitate fish access to the lake. These changes modified the lake's discharge rating curve, representing a discontinuity in the time series of lake stage.

It was shown in Figure 10 that the lake's rating curve was subject to numerous changes in the period from 1988 to present; and Figure 1, prepared by King County, documents this phenomenon from 2001 to present. Hence, the time series of lake stage, even prior to 1998's weir modifications, cannot be considered statistically homogenous.

Here, we investigate whether any specific monotonic trends can be detected as statistically significant, in the pre-1998 time series of daily lake stage data. We perform the following tests for trends:

a) An analysis of trends in the frequency of high lake levels, performed by counting the number of days where stage exceeded fixed threshold values.
b) An analysis of trends in the minimum, mean and maximum, and in specific annual quantiles of daily stage values.

The results of these tests, which are summarized below, are highly significant declining trends in the low end of the daily stage values, i.e., the annual minimum, the 10^{th} percentile and the 25^{th} percentile. But no trends were detected in the median (50^{th} percentile) or higher quantiles, or the maxima.

The rate of linear decline in the minimum annual value of daily stage, estimated from the Sen slope, is 0.016 ft per year, or over half a foot (0.528 ft) in the 33 years of this record. The rate of decline in the 10^{th} percentile of the distribution of daily stages is 0.014 ft per year, or 0.462 ft in the 33 years. The rate of decline in the 25^{th} percentile is 0.011 ft per year, or 0.363 ft in the 33 years.

Searching for an explanation for the declining trends in low lake elevations, we also studied the trends in monthly streamflows in Issaquah Creek, the largest tributary to the lake, and the only tributary for which streamflow records are available for this period. We find declining monthly flows for August and September, the two lowest flow months of the year, for 1965-1997. We also find declining monthly flows for December and January for this period. When the entire period of record for Issaquah Creek streamflows (1964-2012) is considered, the detected trends acquire increased statistical significance, and a trend is detected for February as well.

The strong and highly statistically significant declining trend in the mean inflows in the driest months, August and September, is a likely explanation for the observed pre-1997 declining trend in lake stage.

2.1 Trends in the frequency of high lake stage

Figure A-7 shows the annual counts of lake stage greater than specified high thresholds. No linear trends are immediately apparent, and to be sure, we show in Figure A-8 the results of the Mann-Kendall test for trends on each of these series (except for the highest threshold, 29 ft NGVD, for which the number of observed exceedances was too small). For each threshold in Figure A-8, we cannot reject at the 90% confidence level that the Sen slope is different from zero. Hence, no significant trends in lake level exceedances are detected for this period.

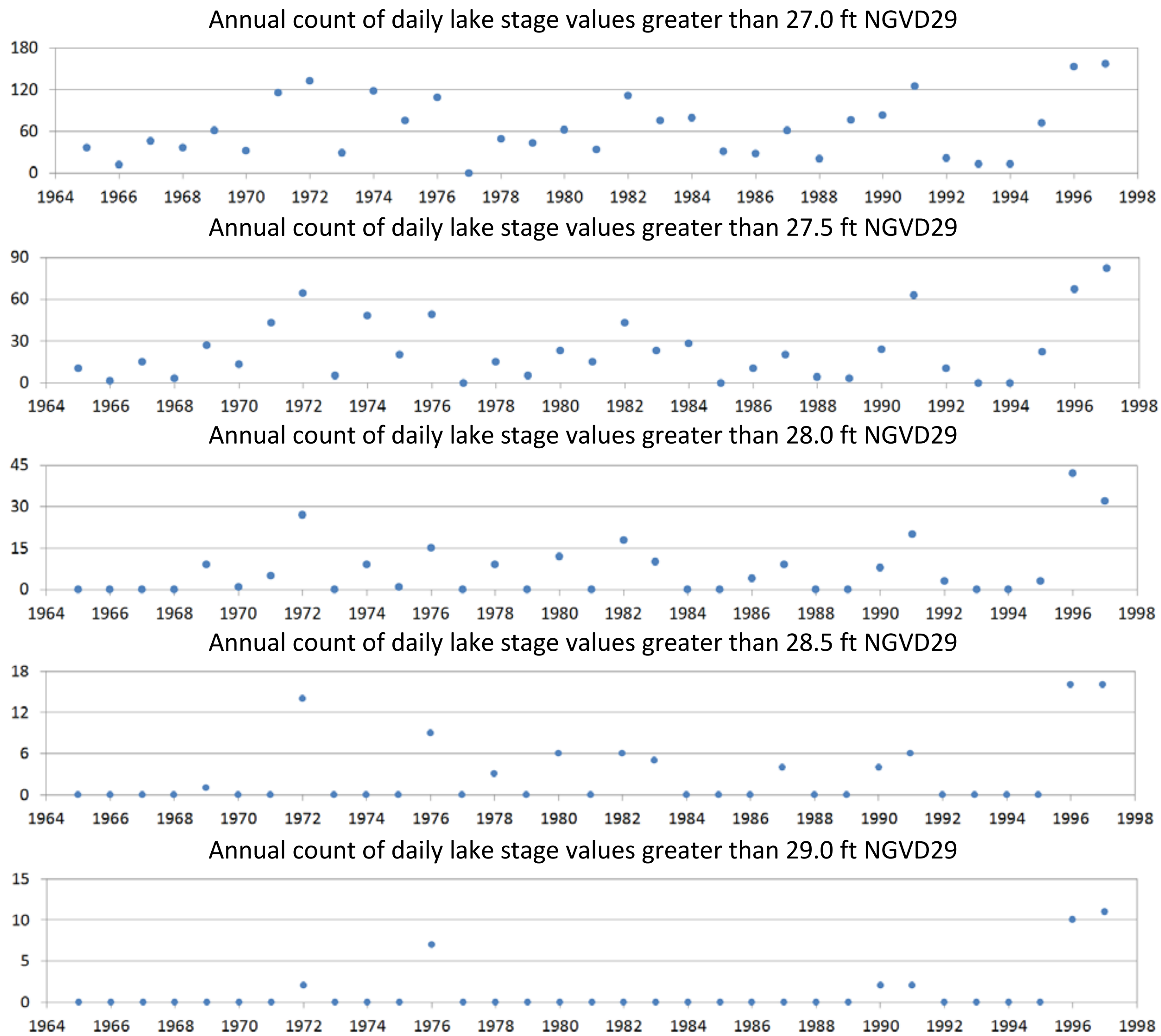


Figure A-7. Lake Sammamish stage exceedance counts by year (1965-1997). Note the different y axis scale among panels.

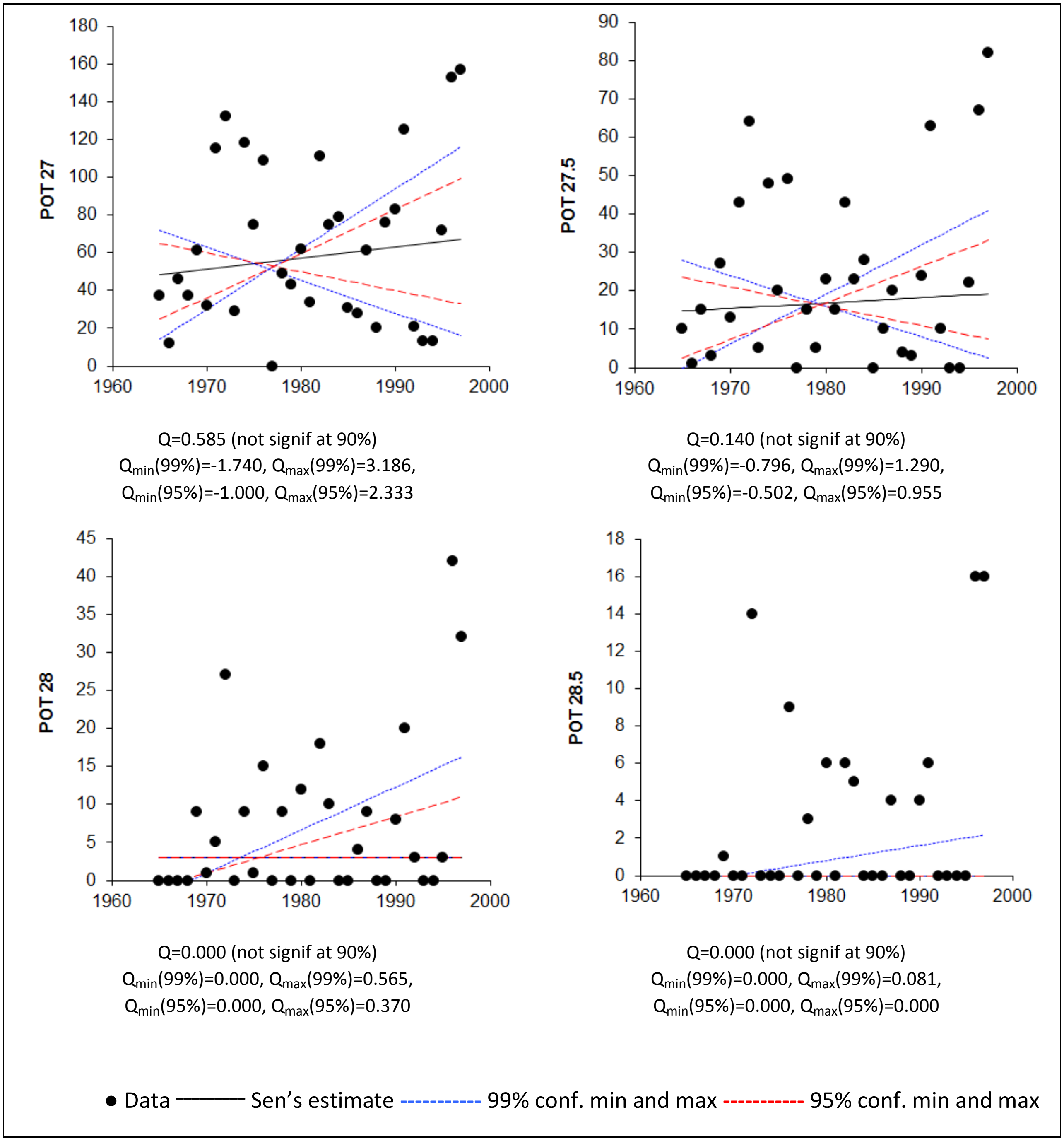


Figure A-8. Mann-Kendall test for trends for lake stage thresholds 27, 27.5, 28 and 28.5 ft NGVD29.

2.2 Trends in the quantiles of daily lake stage

Figure A-9 (same as report Figure 7) shows the annual distribution of daily lake stage, in the form of its minimum, mean, maximum, and the 10^{th}, 50^{th} and 90^{th} percentiles. Figure A-10 shows the results of the Mann-Kendall test for trends for each of these series, and for the series of 25^{th} percentiles, for the period 1965-1997. Declining trends are highly significant (at 99.9% confidence, i.e. α=0.001) for the time series of daily minima and the 10^{th} percentile, and were very significant (at the 99% confidence level, i.e.

α=0.01) for the time series of the 25th percentile. No trends were detected at the 90% confidence level for any of the other series.

The observed decline in low stage values in the lake appears to have been counteracted by the changes implemented in 1998 (Figure A-9).

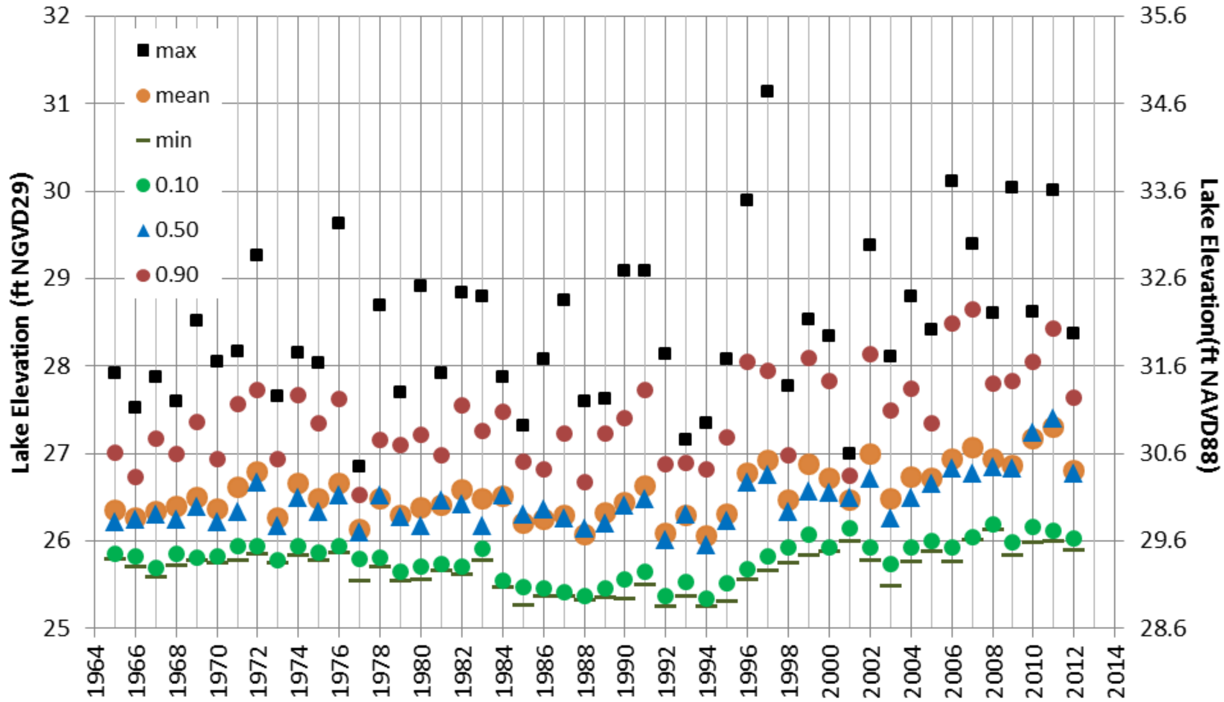


Figure A-9. Annual distribution of daily lake stage. For each water year, we plot the minimum (green dashes), mean (orange dots), and maximum (black squares) of the daily values. We also plot the 10th percentile (green dots), 50th percentile (the median, blue triangles), and the 90th percentile (red dots).

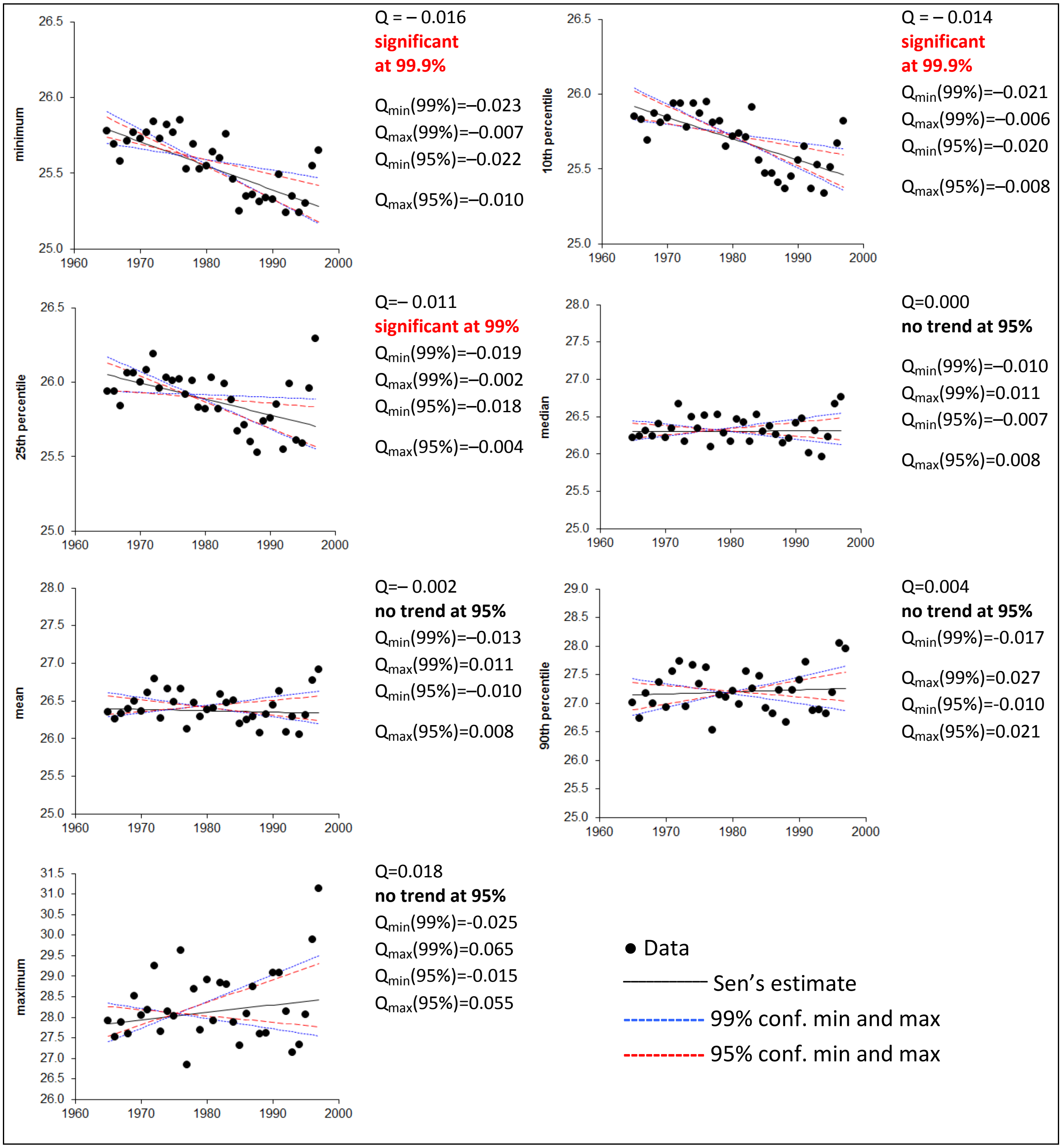


Figure A-10. Mann-Kendall test for trends for the annual time series of daily lake stage minima, mean and maxima, and distribution quantiles, for period 1965-1997. Significant trends are established at 99% level or greater for the minima and the 10th and 25th percentiles. No trends are detected for the other series, at the 90% confidence level.

2.3 Trends in the quantiles of daily discharge from Issaquah Creek

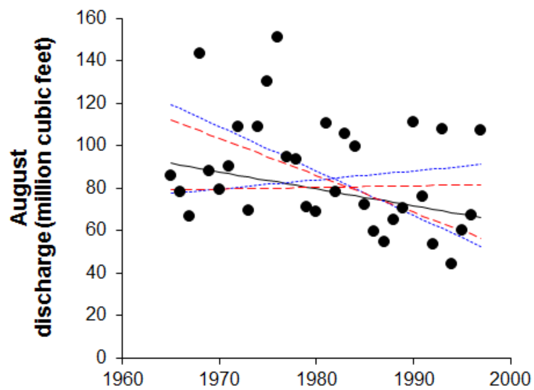
To investigate inflows to the lake as a possible cause for the declining trends in the minimum and lower quantiles of lake stage, we studied the daily quantiles of Issaquah Creek discharge over the same period, 1965-1979.

Figure A-11 shows the results of the Mann-Kendall test for the four months where significant trends were identified.

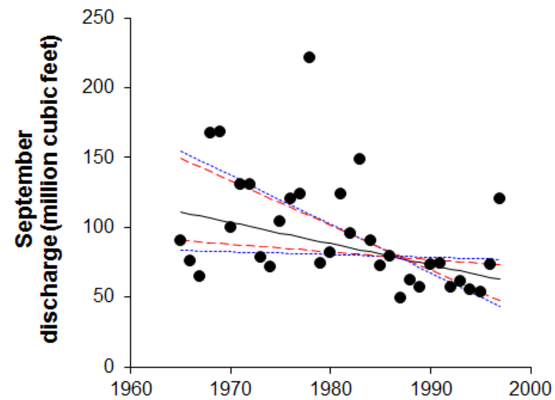
Figure A-12 shows the results of the Mann-Kendall test when the entire 49-year period of record for Issaquah Creek is included, i.e., for 1964-2012. Now, a declining trend for the month of February is also identified as statistically significant. The significance of the September trend is also higher, 99.9%, when the entire period is considered.

The magnitude of the September linear trend is -1.021 million cubic feet (lost) per year (see Figure A-12). Thus, in the 49-year period, the trend originated a decline of about 50 million cubic feet, which represents 55% of the 49-year average streamflow for September (90.3 million cubic feet). For August, the linear declining trend is -0.696 (from Figure A-12), subtracting 34.1 million cubic feet in the 49-year period, which represents 41% of the average August streamflow (83.1 million cubic feet).

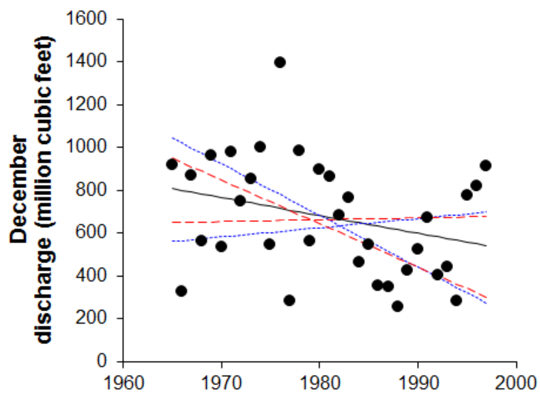
The strong correlation between minimum daily stage in September and Issaquah Creek discharge for August and September is shown in Figure A-13. The strong and highly statistically significant declining trend in the mean inflows in the driest months, August and September, is a likely explanation for the observed pre-1997 declining trend in lake stage.



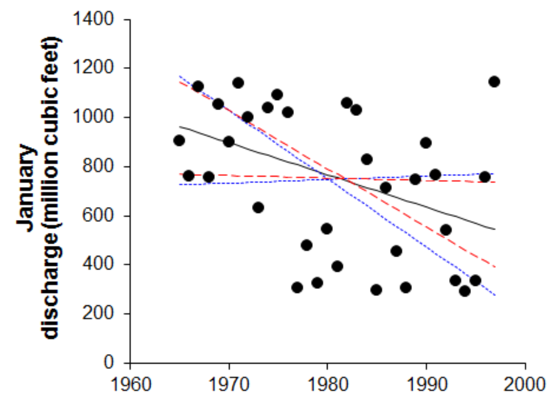
Q=–0.794. **Significant at 90% conf. level.**
$Q_{min}(99\%)$=–2.088, $Q_{max}(99\%)$=0.424,
$Q_{min}(95\%)$=–1.742, $Q_{max}(95\%)$=0.079



Q=–1.515. **Significant at 99% conf. level.**
$Q_{min}(99\%)$=–3.475, $Q_{max}(99\%)$=–0.199,
$Q_{min}(95\%)$=–3.191, $Q_{max}(95\%)$=–0.555



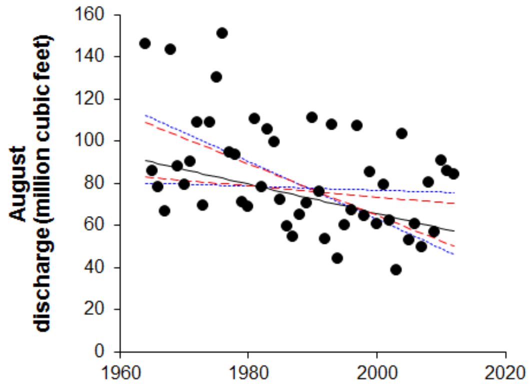
Q=–8.289. **Significant at 90% conf. level.**
$Q_{min}(99\%)$=–24.060, $Q_{max}(99\%)$=4.269,
$Q_{min}(95\%)$=–20.273, $Q_{max}(95\%)$=0.866



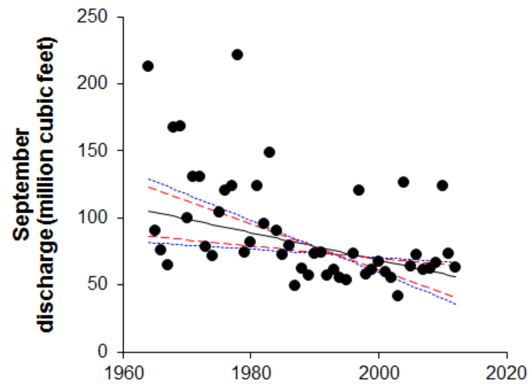
Q=–13.144. **Significant at 95% conf. level.**
$Q_{min}(99\%)$=–27.798, $Q_{max}(99\%)$=1.469,
$Q_{min}(95\%)$=–23.62, $Q_{max}(95\%)$=–1.009

● Data ——— Sen's estimate ----------- 99% conf. min and max ----------- 95% conf. min and max

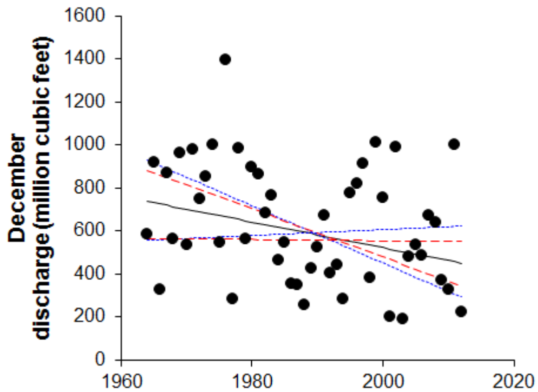
Figure A-11. Mann-Kendall test for trends for Issaquah Creek monthly discharge, for the period 1965-1997. Results are shown only for the four months of the year where the test identified statistically significant trends.



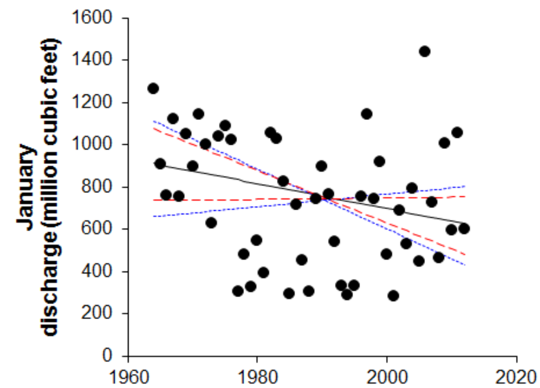
$Q=-0.696$. **Significant at 99% conf. level.**
$Q_{min}(99\%)=-1.372$, $Q_{max}(99\%)=-0.093$,
$Q_{min}(95\%)=-1.220$, $Q_{max}(95\%)=-0.264$



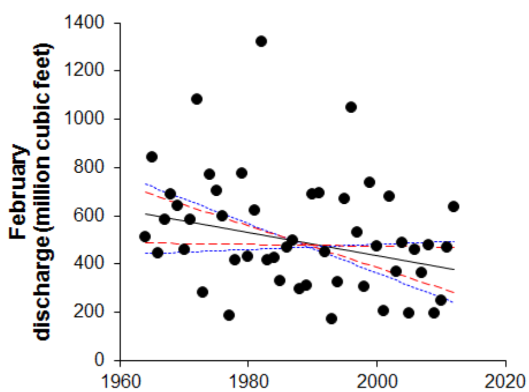
$Q=-1.021$. **Significant at 99.9% conf. level.**
$Q_{min}(99\%)=-1.940$, $Q_{max}(99\%)=-0.305$,
$Q_{min}(95\%)=-1.717$, $Q_{max}(95\%)=-0.459$



$Q=-5.976$. **Significant at 95% conf. level.**
$Q_{min}(99\%)=-13.275$, $Q_{max}(99\%)=1.378$,
$Q_{min}(95\%)=-11.230$, $Q_{max}(95\%)=-0.313$



$Q=-5.921$. **Significant at 90% conf. level.**
$Q_{min}(99\%)=-14.147$, $Q_{max}(99\%)=2.962$,
$Q_{min}(95\%)=-12.340$, $Q_{max}(95\%)=0.359$



$Q=-4.752$. **Significant at 95% conf. level.**
$Q_{min}(99\%)=-10.203$, $Q_{max}(99\%)=1.095$,
$Q_{min}(95\%)=-8.606$, $Q_{max}(95\%)=-0.373$

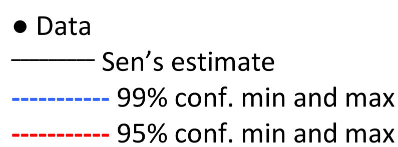


Figure A-12. Mann-Kendall test for trends for Issaquah Creek monthly discharge, for the complete period of record, 1964-2012. Results are shown only for the five months of the year where the test identified statistically significant trends.

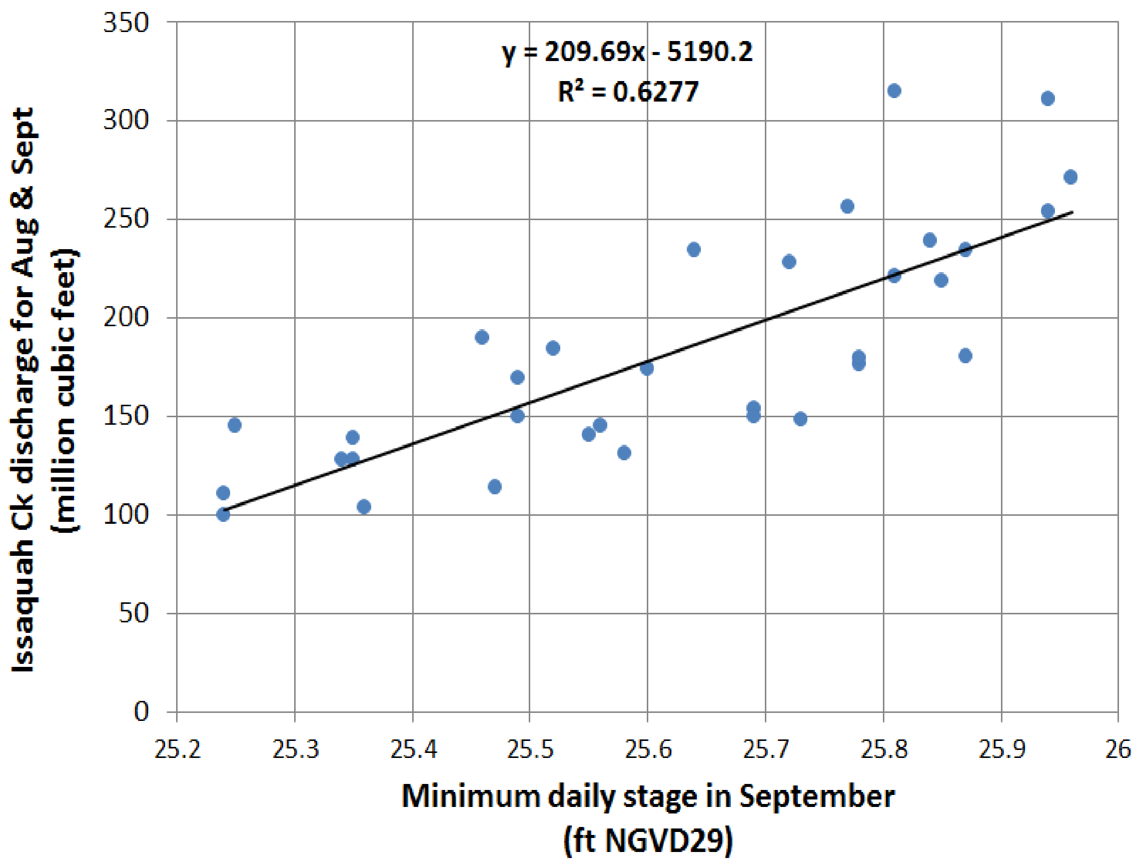


Figure A-13. Effect of Issaquah Creek discharge in the two months of August and September, on the minimum daily stage observed in September.

3 References

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