2.1 HYDROLOGY

2.1 HYDROLOGY

EXECUTIVE SUMMARY

LITERATURE REVIEW

Several historic events and landuse trends have combined to have a profound effect on the hydrology of the Green River. These include four large engineering projects:

- Diversion of the White River in 1906;
- Diversion of the Cedar/Black River in 1913;
- Construction of Tacoma Water’s Headworks Diversion Dam in 1911; and
- Construction of Howard Hanson Dam (HHD) in 1962.

In addition, construction of flood control levees as well as substantial agricultural development and urbanization in the lower basin have also influenced altered the hydrology of the Green River.

The flow regime of the lower Green River was first profoundly changed in the early 1900’s by the permanent diversion of the White River into the Puyallup River for flood control purposes. Soon thereafter (in 1916), the Cedar/Black River was diverted into Lake Washington to facilitate navigation through the Ship Canal. The White and Cedar/Black Rivers combined previously comprised approximately 60 percent of the watershed in total acreage, and contributed a commensurate amount of flow to the lower Green/Duwamish River. Diversion of the White River in particular radically reduced summer low flows and altered the lower Green River’s sediment supply (Dunne and Dietrich 1978). The White River, being glacially fed, tends to have higher summer flows, and carries a greater sediment load (per unit drainage area) than the lower gradient, non-glacial Green River. Recent groundwater investigations indicate that the White River is still connected to the Green River via subsurface flows, providing approximately 56 cfs to the lower river in the late summer (Pacific Groundwater Group 1999).

In 1911, the City of Tacoma constructed a diversion dam at RM 61 on the mainstem Green River to capture water for municipal and industrial water supply. The dam and diversion were completed in 1913. Since that time, Tacoma has been almost continuously diverting up to 113 cfs from the mainstem Green River to meet the needs of the rapidly expanding population in Puget Sound. This diversion constitutes approximately 12 percent of the average annual flow at Palmer, the point of diversion. A portion of this water may be replaced during periods of high turbidity by water drawn from a well field that taps the North Fork Green River aquifer.

In 1961, construction of HHD again substantially changes the hydrologic regime of the Green River. Floods greater than approximately 12,000 as recorded at the USGS at Auburn cfs (formerly a two-year return interval event) have been prevented, while the duration of moderate flows (3,000 to 5,000 cfs) has increased due to metered release of floodwaters stored behind the dam. Howard Hanson Dam is also authorized to store water during the summer to augment late summer low flows. Seasonal storage has inundated about 7.5 miles of former riverine habitat in the Upper Green River sub-watershed. Filling of the conservation pool to target levels during the late spring temporarily reduces flows and has historically intercepted freshets that were important mechanism for initiating and expediting the downstream migration of juvenile salmonids.

More recently, urban development in the lower basin has resulted in substantial increases in stormwater runoff from small tributary streams. This in turn has contributed to larger and more frequent peak flows during the winter, and reduced recharge of shallow aquifers that formerly sustained flows during the late summer and fall. Similar effects, though not as severe, occur in the middle and upper watersheds as a result of land clearing for residential development, agriculture and forestry. The overall effect of development on flows in the lower mainstem Green River is difficult to discern due to the overwhelming changes in flow resulting from the diversions, channelization, and HHD.

"NATURAL FLOW ANALYSIS"—HYDROLOGY ADDENDUM

In order to better understand the effects of these two significant public works projects on downstream hydrology, a trial analysis of hydrologic change in the Green River was conducted. This analysis is included as an addendum to this chapter. The primary goals of this analysis were twofold: 1) to determine whether such an analysis is practical and feasible for assessing hydrologic impacts on Green River ecology; and 2) to identify clear areas of hydrologic alteration and their potential ecological implications.

The evaluation focused on the middle Green River between Palmer and Auburn, and addressed only the effects of the operations of HHD and the City of Tacoma's flow diversion. No attempt was made to evaluate "historic" conditions prior to the White and Cedar Rivers being diverted from the watershed, or prior to logging practices commencing above HHD.

The technique utilized considers all major aspects of the flow regime having the potential to affect ecological processes and habitat conditions in the study reach. Given the relatively new nature of this type of analysis, results are preliminary and the methodology should be viewed as a tool that can be modified to improve its relevance to evaluation of Green River ecology.

The Range of Variability approach developed by Richter et. al. (1996, 1997) was modified for application to the Green River. The period of record used was 1964-1995. Flows for the "with-projects" condition were based on the measured data from the USGS gage site at Palmer. The natural or "without-projects" flows are based on a simulation using the Howard Hanson Reservoir inflow data adjusted for reservoir storage and routing. The two data sets are consistent in terms of underlying climate and land use conditions.

Several trends are evident between flow conditions with and without the HHD and Tacoma Public Utilities projects. Median flow values were lower and there was an overall downward shift in flow distributions for the with-projects scenario. These effects apparently result from the diversion of up to 113 cfs from the river by the TPU project and from the reduction in flood peaks due to HHD.

One of the two original congressionally authorized purposes for HHD was low flow augmentation. The analysis indicates that flow augmentation by HHD does not fully overcome the flow reduction effects of the Tacoma diversion during low flow periods. The low flow conditions in the river last longer than they would without the projects in place and the annual minimum flow tends to occur two weeks earlier than without the projects.

Flood flows were substantially lower under the with-projects scenario. Peak flows in the 1964-1995 period likely would have ranged up to 29,000 cfs without the projects in place (based on the natural flow simulation), and 16 percent of the annual peaks would have been expected to be greater than 11,000 cfs at Palmer. With the projects in place, no annual peak flows have exceeded 11,000 cfs. Managed flood peaks also lasted for longer periods of time under the with-project scenario, albeit at greatly reduced levels.

The effects of the two projects are summarized in Table Hydro-ES1 below.

Table Hydro-ES1. Summary of "Natural Flow Analysis" Findings.

Hydrologic Characteristic	With Projects	Potential Ecological Implications
Annual minimum and summertime low flows	Flows less than 302 cfs occured 49percent more often and summertime means and annual minimum extremes were consistently longer	• Reduces spatial habitat for rearing • Decreases water depth in riffles, glides and pools. May constrain upstream adult chinook migrationReduces water velocity, may be constraining downstream juvenile movement (e.g., outmigrant survival rates of coho tend to decrease with decreased flows)Shallower water can lead to higher temperatures where temperatures already can exceed salmon preferences in the Green River • Decreases wetted width of river available for spawning, forcing chinook to spawn closer to the thalweg, where scour potential is generally greater. • May create adult chinook passage problems from mainstem into Newaukum Creek
Timing of annual minimum flow	The annual minimum flow occurred two weeks earlier, in late August rather than mid-September	• May affect timing of upstream adult migration • May create warmer, more stressful instream conditions where temperatures already can exceed salmon preferences
Annual maximum flows (flood peaks)	Flood peaks were reduced, with no flood flows above 11,000 cfs at Palmer with the projects in place (compared to one day flows ranging up to 18,000+ cfs without projects (and peak flows even higher) and exceeding 11,000 cfs in 1 out of every 6 years)	• River has less ability to create new side channel habitat, reducing habitat for salmon as well as recruitment of gravel from the floodplain • River has less ability to maintain existing side channels • River has less ability to recruit wood into the channel, reducing overall habitat quality • River margin habitats are less dynamic and becoming artificially stable, reducing gravel recruitment from stream margin
Flood durations	Durations of moderate flood flows (greater than 5925 cfs) were longer by 39percent	• May increase frequency or duration of scour of river bed gravel. Effects are compounded as fewer side channels (where scour would be less) are being created so more of the population spawns in the mainstem

KEY FINDINGS: IMPACTS TO SALMONIDS RESULTING FROM HYDROLOGIC ALTERATION

UPPER GREEN RIVER SUB-WATERSHED (RM 64.5 TO HEADWATERS)

Upstream Migration

- Subsurface flows have been observed in the North Fork Green River during late summer (Noble 1969; Hickey 2000b), and could prevent salmonids from entering the river or moving upstream. Operation of the North Fork well-field by Tacoma could reduce flows in the North Fork, although there is currently insufficient data on the extent of this potential impact.

Spawning and Incubation

- One model suggests that timber harvest related disturbances have been extensive enough to cause peak flow increases capable of modifying channel conditions (USFS 1996; O'Connor 1996; Wetherbee 1997) and mainstem reaches just upstream of the Lester WAU have recently experienced scour to a depth sufficient to cause redd mortality during high flows (Fox and Cupp 1996).

- The inundation of up to 7.7 miles of mainstem and tributary habitat has resulted in lower water velocities, decreased oxygen levels, and increased sediment loads in the redd environment, which can result in embryo and larval mortality. The associated decrease in temperature with the increase in water depth can result in a delay of egg maturation.

- Howard Hanson Dam and the Headworks Dam have resulted in the inaccessibility of over 100 miles of combined mainstem, tributary and side channel spawning habitat to anadromous salmon.

Juvenile Rearing

- Construction of HHD has resulted in a net loss of 7.7 miles of mainstem and tributary rearing habitat (side channel habitat undetermined) due to inundation when operated at full pool. This area has been converted into rearing habitat that fluctuates unnaturally from a lake to free flowing depending on flood control responsibilities.

Downstream Migration

- Downstream migrating salmonid smolts, especially chinook, are delayed within the reservoir behind HHD and subject to increased mortality in the reservoir and through the dam bypass pipe and gates.

MIDDLE GREEN RIVER SUB-WATERSHED

Upstream Migration

- Since 1913 the Tacoma water withdrawals at the Headworks have lowered summer low flows in the mainstem. Howard Hanson Dam summer low flow augmentation (since 1964) has helped to increased these flows but not to natural, pre-diversion levels. Low flows in the late summer have only met instream flow requirements 9 out of the last 30 years (30percent). Tacoma's First Diversion Water Right Claim (FDWRC) of 113 cfs is not constrained by these minimum instream flow requirements.

- Refill of the HHD conservation pool in the spring has historically prevented or truncated spring freshets. The lack of freshets, especially during the spring reservoir refill period may delay steelhead upstream migration.

Spawning and Incubation

- Alterations in the natural flow regime during HHD refill operations may adversely impact spring spawning and incubation success in off-channel habitats that become disconnected.

- The dam flood flow manipulations result in an increase in the duration of flows that scour spawning gravel from the streambed.

- Late summer flows downstream of the Headworks (1911) diversion compel many chinook to spawn towards the thalweg rather than the margins, increasing the probability of egg loss due to streambed scour during higher winter flows.

- Late summer low flows and associated shallow water over many riffles increase the energy expenditure of upstream migrating adult chinook.

- Late summer low flows and associated shallow water can reduce the number of chinook that spawn in the downstream ends of side channels.

- Summer low flows increase the difficulty adult chinook have moving from the Green River into major spawning tributaries such as Newaukum Creek.

Juvenile Rearing

- Lower than normal summer low flows have reduced the amount of rearing habitat and exacerbated high summer water temperatures.

- Refill operations at HHD have reduced the frequency of side-channel connectivity, which would increase the probability that juvenile salmonids may become stranded in side channels that become disconnected from the mainstem. Juvenile chinook have been observed utilizing side channel habitats in the mainstem during the spring (Jeanes and Hilgert 2000).

Downstream Migration

- Spring refill operations at HHD have reduced flows and prevented spring freshets, prolonging downstream migration of juvenile salmonids. This makes juvenile salmonids more susceptible to predators and adverse water quality conditions. Green River Hatchery chinook smolt releases have been shown to have higher survival to the Duwamish with increasing flow; only 40 percent of the smolts released survived when flows were approximately 650 cfs at Auburn, while survival rates between 70 and 100 percent were observed at flows higher than 2,000 cfs (Wetherall 1971).

LOWER GREEN RIVER SUB-WATERSHED

Upstream Migration

- The diversions of the White River and Cedar/Black Rivers altered the migration routes of upstream migrating salmonids

- The combined diversion of the White River and Cedar/Black Rivers reduced the drainage area of the Green River basin by almost 60 percent. Diversion of the White River reduced summer flows in the lower Green River basin by roughly 50 percent. This results in the loss of physical habitat area such as size of pools, depth of riffles and an increase in temperature .that could delay migration and harm fish.

Spawning and Incubation

- Alterations in the natural flow regime during HHD refill operations may adversely impact spring spawning and incubation success by disconnecting off-channel habitats. .

Juvenile Rearing

- Low summer flows adversely impact the amount of rearing habitat and increase high summer water temperatures.

- Juvenile chinook, coho, steelhead, chum and cutthroat salmonids have been observed utilizing side channel habitats in the mainstem during the spring (Jeanes and Hilgert .2000). Refill operations at HHD have reduced the frequency of side-channel connectivity, which would increase the probability that juvenile salmonids may become stranded in side channels that become disconnected from the mainstem.

- The diversion of the White and Cedar/Black Rivers and construction of revetments reduced the channel width and caused the Green River to form a new, lower floodplain, cutting of access to former off-channel rearing habitats.

- The amount of urbanization increases the frequency, magnitude and duration of stormwater runoff that adversely impacts salmonid rearing habitat.

KEY FINDINGS--MAJOR TRIBUTARIES

Upstream Migration

- The affects of urbanization and groundwater withdrawals have reduced summer low flows, which may delay the upstream migration of adult chinook salmon in Newaukum and Soos Creeks.

Spawning and Incubation

- Impervious surfaces resulting from urbanization increases the volume of stormwater discharged into a stream for a given storm event. This action increases the height of peaks and creates new peaks where none previously existed, potentially increasing the frequency of scouring and deposition. This further reduces egg and alevin survival.

Juvenile Rearing

- Increases in urbanization and groundwater withdrawals have reduced summer low flows, reducing the amount of available salmonid rearing habitat and exacerbating increases in summer water temperatures (water quality degradation).
- As urbanization increases, the volume of stormwater discharged into a stream for a given storm event also increases. This action increases the height of peaks and creates new peaks where none previously existed potentially increasing the downstream displacement of emergent fry and reducing quality of overwintering habitat.

DATA GAPS

- There is little information available to assess the historic impacts of operation of Tacoma's North Fork well field on fish passage in the North Fork Green River
- The results of the trial "Natural Flow Analysis" suggest several data gaps where additional research into flow records and/or records of operations may improve these conclusions. Two of the most important are listed below:
  - Howard Hanson Dam operations--The analysis of managed conditions is wholly based on the measured flows at Palmer over the period of record, even though HHD operations have changed during that time period. In particular, changes in spring refill timing and flood ramping rates may have an impact on downstream hydrologic conditions. The model could be revised to clearly define HHD operating guidelines and simulate managed conditions over the entire time period as if current operations had prevailed.
  - TPU flow diversion records and protocols--Review of diversion records would improve the evaluation of diversion impacts during extreme low flow periods by isolating the effects of the diversion from HHD flow augmentation operations. From a comparison of mean monthly flows for with-and without-projects conditions, it is clear that the entire 113 cfs diversion right was not always implemented.

METHODS AND APPROACH

Hydrology (referring to the quantity and movement of water through an ecosystem) is one of the principal processes responsible for creation and maintenance of aquatic habitat. The volume of water in the Green River and its tributaries at various times during the year, and the degree to which this has been altered by development, operation of dams, and other practices, has profound implications for salmonid population viability. This chapter describes current and historic conditions in the Green River watershed, with a principal focus on the mainstem Green River and major tributaries. The potential effects of proposed projects and possible future landuse changes that may alter hydrologic conditions in the future are not considered here.

Two principal approaches have been taken to evaluating the hydrology of the Green/Duwamish River River. The main body of this report describes existing and historic conditions based on information contained in previous studies and literature and the report addendum describes a trial approach to analyzing natural streamflows in the Green River. Together, the results of these approaches were used to identify and evaluate hydrologic impacts on fish.

In the past, efforts to protect aquatic species from hydrologic impacts have largely focused on the setting of minimum instream flows. Recent research however, emphasizes the importance of the entire hydrologic cycle within which salmonids (Richter et al. 1996; Poff et al. 1997). This view considers the evolved range of flow variation in a naturally flowing river: the magnitude, frequency, timing, duration and rates of changes of various individual and seasonal flow events. Thus, both the literature based review and the trial natural flow analysis conducted for the Green River were designed to evaluate this broad range of flow characteristics.

To facilitate these analyses, the mainstem Green River Basin has been subdivided into five sub-watersheds: 1) the Upper Green River sub-watershed (upstream of the HHD at RM 64.5); 2) the Middle Green sub-watershed (RM 32 to RM 64.5); 3) the Lower Green River sub-watershed (RM 11 to RM 32); 4) the Green/Duwamish Estuary (downstream of RM 11); and major tributaries (Soos Creek and Newaukum Creek) (Figure HYDRO-1). This partitioning reflects divisions of the system by both natural and human influences, and to a certain extent, by fish use.

The following sections discuss major hydrologic impacts to the mainstem Green River drainage area by sub-watershed. Impacts are generally classified as occurring due to flood control projects, water use or land use activities.

RESULTS

UPPER GREEN RIVER SUB-WATERSHED (RM 64.5 TO RM 93)

WATER USE AND DIVERSIONS

The Upper Green River sub-watershed is primarily forested, with few residences and virtually no residential development. The primary water use in the upper watershed consists of the City of Tacoma's (Tacoma) North Fork Well field. The following discussion of the North Fork well field was provided in a draft HCP recently completed by Tacoma (Tacoma 1999).

Tacoma operates a well-field that taps the North Fork Green River Aquifer, using the water to partially replace surface flows when the turbidity of the Green River reaches 3 NTUs and completely replace surface flows at turbidity levels of 5 NTUs or greater. The well field, developed in 1977, consists of seven wells that can be used to withdraw water from an unconfined aquifer at depths ranging from 65 to 103 feet. Water from the well field is pumped into a pipeline that flows into a 10-million gallon reservoir located near the Tacoma Headworks facility.

The well field is used to replace surface water withdrawn from the Green River at RM 61.5 when turbidity in the river is high. High turbidity in the Green River usually occurs in association with high runoff and increased stream flows, thus use of the well-field generally coincides with high flows in both the mainstem Green and North Fork Green River during the winter and spring. Over a five-year period in the 1960s, periods of high turbidity (>5NTUs) in the Green River, during which withdrawal from the well field would be required, averaged 85 days per year (Table Hydro-1). Periods when well use would have been required have occurred in September; however, those September turbidity events occurred when flows in the North Fork and mainstem Green River were high (Noble, 1969).

Table HYDRO-1. Summary of Average Daily Flow in the North Fork Green River and Expected Well Demand from the North Fork Well Field by Month.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Avg. Daily flow(cfs) [1]	147	124	92	117	121	73	26	12	24	38	96	169
Days of well use (avg) [2]	15.2	10	6.2	8.8	11	5.4	0	0	2.6	2.4	10.2	13
Days of well use (range)	4-25	0-28	0-18	0-23	0-20	0-20	0	0	0-13	0-4	7-13	7-19

[1] Mean average daily flow at USGS gage 12105710 North Fork Green River near Lemolo, Washington for the period from July 1965 to September 1982.

[2] Average number of days per month that well use would be required, based on the number of days when turbidity exceeded 5 NTU's measured at the Headworks over a five year period in the 1960's (Noble 1969).

The North Fork Green River aquifer is fed by water that infiltrates from the North Fork Green River from where it enters the broad valley of the ancestral Green River (approximately RM 3.0) until the point where the stream intersects the water table near the well field. The recharge rate is directly related to river stage in the North Fork Green (Robinson, 1974). The mean discharge of underflow is estimated to be 60 cfs (Noble, 1969), and may reach as much as 150 cfs during winter months (Robinson, 1974).

Withdrawals from the well field are limited to the quantity available from aquifer underflow plus depletion of aquifer storage (Noble and Balmer, 1978). The aquifer is small, and recharges quickly during wet periods. However, the infiltration rate is less than the aquifer transmissivity rate, and the wells are thus able to fully intercept the underflow (Noble and Balmer 1978). The small amount of aquifer storage and lack of recharge limits the North Fork well field as a source of water during dry periods when flows in the North Fork Green River are low. Operation and testing of the wells indicates that the well field can sustain approximately 60 million gallons per day (93 cfs) under very wet conditions where recharge of the aquifer occurs at a high rate during the pumping period, and can probably sustain 24 million gallons per day (37 cfs) continuously under all except the driest conditions.

Investigations of the lower North Fork Green River have shown that the majority of flow within the reach downstream of the North Fork well field is supplied by emerging groundwater during the late summer and early fall (Noble 1969). As surface flows decline, the proportion of flow provided by underflow increases, and in extreme cases may maintain flow within the lower North Fork Green River channel even when upstream reaches are dry. Instream flows supplied wholly or partly by groundwater outflows provide habitat and temperature refugia for fish during the late summer and fall low flow period.

FLOOD CONTROL

Howard Hanson Dam is a federally funded and operated flood control project on the Green River located at RM 64.5, and spans an area of the Green River downstream of Eagle Gorge[1], a narrow canyon with nearly vertical rock walls. Construction began in February 1959, and the dam went to operation on Christmas Day of 1961[2]. Construction of Tacoma's Headworks Diversion Dam (Headworks) in 1913 had blocked upstream fish passage at RM 61.5, approximately three miles downstream from HHD, thus no upstream fish passage facilities were originally incorporated into HHD.

HHD is a subsidiary earth-filled structure composed of rolled rock fill, sand and gravel core, drain zones, and rock shell protection (USACE 1998). The dam is 960 feet thick at the base decreasing to 23 feet thick at the crest. The embankment is 235 feet high and 500 feet long and has an inclined core of sand and gravel material. The total length of the dam, including the spillway and abutments, is 675 feet.

The intake structure includes trashrack bars, a deck for debris removal, one tractor type emergency gate, and gate hoist equipment located in the gate tower. The outlet structure consists of a gate tower and intake structure with two tainter-type gates, a concrete horseshoe-shaped outlet tunnel, a gate-controlled bypass, and a stilling basin. The 900-foot-long, 19-foot-diameter flat bottom horseshoe-shaped outlet tunnel passes normal flow released for project regulation. The tunnel is controlled by two 10-foot-wide by 12-foot-high regulating tainter gates at the bottom of the reservoir pool (elevation 1035 feet) above mean sea level (MSL). Low-flow releases during the summer conservation period are made through a 48-inch bypass intake located about 35 feet above the bottom of the pool. This outlet has a capacity of approximately 500 cfs at maximum conservation pool (elevation 1141 feet). Flows are regulated manually by adjusting gate controls at the dam under direction of the U.S. Army Corps of Engineers Water Management Section.

The gate-controlled spillway is anchored in rock on the left abutment and in a concrete monolith adjacent to the embankment. The spillway is a concrete ogee overflow section with two 30-foot-high by 45-foot-wide tainter gates to control major flood flows and prevent overtopping of the dam. The lowest elevation of the gates is 1,176 feet. The downstream chute has a curved alignment and is paved for a distance of 712 feet downstream from the weir. The tainter gates

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[1] Eagle Gorge was a canyon located about 1.75 linear miles (not RM) southeast of Howard A. Hanson Dam.

[2] USGS Water Data Reprt WA-96-1, p. 178, reports that the earth-fill dam was completed 31 March 1962, and that "storage began Dec. 5, 1961."

permit storage to elevation 1,206 feet without spillway discharge. The maximum spillway discharge is 115,000 cfs at the spillway design flood pool elevation. In an extreme flood situation, water can be released over the spillway through the gates. To date, use of the spillway has not been required.

The reservoir behind the dam collects runoff from the 220 square mile Upper Green River Basin. In normal years, the reservoir is drawn down to an elevation of about 1070 feet in November when the summer low flow period is obviously over, significantly reducing the pool area. During winter, the reservoir is kept nearly empty, and the river flows through the gate-controlled outlet tunnel at the dam's left abutment. Howard Hanson Dam was designed to provide flood protection up to the 500-year event or the equivalent of a peak inflow to the reservoir of 65,000 cfs, and provides 106,000 acre-feet of flood control storage. The reservoir is kept as low as possible during the late fall and winter flood season to maximize flood control storage, thus during that time HHD is essentially a run-of-the-river facility. As the river rises during storm events, water is impounded. During flood regulation, the project is typically operated to limit flows at Auburn below 10,000 cfs as inflows to the reservoir are rising, and to below 12,000 cfs as inflows recede. As inflows to the reservoir decline, the water impounded in the reservoir is released at a rate sufficient to prevent a drastic drop in the stage in the river downstream, which could result in bank sloughing or fish stranding. The details of HHD operational requirements are found in Table HYDRO-2 and Appendix HYDRO-1. Flood control operations are conducted in accordance within the parameters of the project's congressional authorization. (so there is little flexibility to operate for other purposes during the flood season.)

Table HYDRO-2: General Ramping Guidelines Followed by the Army Corps of Engineers for Operation of HHD.

Tailwater change	No more than 1 foot/hour. Attempt to limit to 0.2 feet/hour during normal operations.
Auburn stage	Attempt to limit Auburn stage drop to 1 foot/day during recession.
Refill considerations	Attempt to follow WDFW guidelines for ramping criteria.

The probability of flooding greatly diminishes by late February, and the dam begins its second major function: water conservation. Usually, the reservoir begins to fill in mid-April to a maximum pool elevation (1141 feet), to provide summer and early fall low flow augmentation. At full pool (1141 feet), the reservoir inundates approximately 4.5 miles of mainstem Green River habitat, and about 3 miles of stream habitat in the North Fork Green River and other tributaries.

The original authorization of HHD provided for fishery enhancement by storing water through the summer, then releasing it to augment low flows occurring in the late summer and fall. The low flows are a result of seasonal variation and water withdrawals such as those shown in figure Hydro-4. Historically, refill of the reservoir usually began between late April and June. In recent years, the start of refill is determined each year depending upon conditions of that specific water year. The Army Corps of Engineers coordinates refill with federal, state and local fisheries agencies, the Washington Department of Fish and Wildlife and the Muckleshoot Indian Tribe.

During refill, outflow is reduced and the reservoir allowed to partially fill to elevation 1141 feet in order to provide a summer conservation pool for low flow augmentation. The reservoir contains approximately 25,000 acre-feet of water at this elevation, which is the amount of water needed to assure flows of at least 110 cfs at Palmer (downstream of Tacoma's diversion) with 98percent reliability. Filling the reservoir above elevation 1141 is not regularly practiced, as this inundates otherwise dry upstream habitat. Filling also affects downstream habitat by interrupting the natural river flow regime.

In combination, HHD and Tacoma's Headworks result in the loss of anadromous salmon accessibility to 29.8 miles mainstem and 6.9 of mainstem side channels as well approximately 70 miles of tributary channels. All but 3.3 miles of mainstem and 2.8 miles of tributary habitat is located upstream of the HHD (J. Cutler pers comm. 1999). Since 1980, juvenile salmonids have been released into the Upper Green River sub-watershed. More recently, at temporary adult fish trap has been constructed on the right bank at the Headworks. This trap is used to capture adult steelhead for transport upstream of HHD and artificial propagation. A detailed description of up and downstream migration and passage barriers associated with these projects is provided in the Fish Passage chapter of this report.

A small storage pool is maintained behind the dam year round, including during the winter drawdown, to capture suspended sediment. This storage pool is called the turbidity pool, and it currently permanently inundates approximately 1.8 miles of stream habitat, including 1.5 miles of mainstem channel (USACE 1998). At the normal summertime high pool elevation of 1141 ft MSL, the reservoir inundates approximately 7.2 miles of stream habitat. The average total length of time the pool is held at or above 1141 ft is 79 days, and generally occurs between May 15 and July 30. The reservoir pool may be filled to a maximum elevation of 1147 feet MSL for debris collection, and is typically at that level for approximately two weeks (USACE 1998).

Inundation converts formerly free-flowing stream habitats to lake-like conditions during flood control operations and spring refill. Water depth increases, water velocity is reduced, and the temperature regime and dissolved oxygen content change. The primary effects of inundation are a substantial reduction in vegetative cover, bank stability and the number and structure of pools, and an increase in the amount of fine sediment in riffles (Wunderlich and Toal 1992).

In addition to inundating habitat formerly used by anadromous and resident fish, operation of HHD has modified physical habitats in portions of the river that are seasonally free-flowing. Physical habitat alterations are discussed in the Hydromodification chapter of this report.

LANDUSE

Since 1914, when the City of Tacoma entered a cooperative agreement with the federal government for the purpose of protecting the City's water supply, access to lands owned by Tacoma in the upper basin has been limited, except for fire protection, forest management activities and to provide access to United States Forest Service (USFS) lands. Lands managed by the USFS in the upper watershed may be accessed via Stampede Pass, and are currently used primarily for recreation.

Removal of forest vegetation can cause changes in the amount of precipitation that reaches the ground and in the rate of snowmelt (Harr et al 1975; Troendle and King 1985; Haupt 1979; Harr 1981). Roads and skid trails convert subsurface flow to surface flow and compact the soil, increasing surface runoff (Megahan 1983). Using a model that predicts flow increases based on the amount of mature forest cover by elevation zone, and local climatic data, the WDNR watershed analyses completed for the Lester, Upper Green and Sunday Watershed Administrative Units (WAUs) in the Upper Green River sub-watershed suggested that few tributary basins had experienced peak flow increases greater than 10 percent as a result of existing timber harvest operations (O'Conner 1996; Wetherbee 1997). Draft analyses completed to date for the Howard Hanson/Smay WAUs reach the same general conclusion (Ryan 1999). Ten percent is generally considered the threshold of concern for peak flow increases according to the DNR Watershed Analysis hydrology model.

In contrast, the Mount Baker-Snoqualmie National Forest (MBSNF) uses the amount of disturbed area in a basin to determine whether increased peak flows have the potential to alter channel conditions. Based on an empirical relationship that suggests peak flow increases which impact stream channels occur when 12 percent of a drainage basin has compacted soils (i.e. roads and skid trails), the MBSNF has determined that harvest-related disturbance within the Upper Green River sub-watershed is extensive enough to cause peak flow effects in a number of subbasins (USFS 1996). Increased peak flows, particularly in combination with high sediment supply, increase the risk of bed scour. While the results of these assessments are somewhat contradictory, mainstem reaches just upstream of the Lester WAU have recently experienced scour to a depth sufficient to cause redd mortality during high flows (Fox and Cupp1996).

MIDDLE GREEN RIVER SUB-WATERSHED (RM 32 TO 64.5)

WATER USE AND DIVERSIONS

The principal consumptive use of water from the mainstem Green River is the City of Tacoma municipal water supply accounts for 57percent of the Green River surface water rights (Figure HYDRO-4). Tacoma began diverting water from the Green River in 1913 with the completion of the Headworks. Tacoma's average diversion increased from 62 cfs in 1913 to about 100 cfs in 1953, and has remained at that level since 1953. Water is continually diverted from mainstem Green River except at times of excessive turbidity (>5NTU's), when Tacoma uses groundwater pumped from its North Fork Green River well fields. In 1985, Tacoma was granted a Second Diversion Water Right (SDWR) to an additional 100 cfs. Water available under the SDWR has not yet been utilized. Other consumptive water uses, including mining and irrigation, represent the remaining 43percent of allocated water rights in the mainstem (Figure HYDRO-4).

Tacoma provides approximately 62 million gallons of water per day to nearly 83,000 customers in Tacoma, Pierce and King Counties (Tacoma Water 1999). Commercial and industrial customers use the majority of Tacoma's municipal water supply (Figure HYDRO-4), and one customer, the Simpson Tacoma Kraft Company, accounts for the majority of commercial/industrial use (65percent of Commercial/Industrial; 33 percent of total) (Tacoma Water 1999). As a result of a severe drought in 1987, Tacoma Water increased its focus on water conservation. In 1998, average daily consumption was down 15 percent from 1989 levels, despite a 10 percent increase in customers (Tacoma Water 1999).

A comparison of the actual measured flows at Palmer and Auburn with the projected natural flows over the period from 1964 to 1996 indicated that the average seven-day low flow was 18 percent lower than it would have been without the Diversion and HHD at Palmer, and 7 percent lower than it would have been without the Diversion and HHD at Auburn (Table HYDRO-3). While changes in climate and inflows from tributary streams may have influenced these flows, much of this decline can probably be attributed to Tacoma's diversion. Preliminary results also indicate that timing of minimum flows in the vicinity of Palmer has become more variable, and now occur in the first week of September as compared to the third week in September under the natural flow regime (D. Hartley, 1999). The addendum to this chapter contains a detailed comparison of the modeled natural and with-project flow regimes.

Table HYDRO-3: Estimated natural and regulated seven-day low flow and annual minimum flow for the period of 1964 to 1996, compared to the actual flow at the Auburn and Palmer USGS gages on the Green River, Washington.

	Auburn Gage	Auburn Gage	Palmer Gage	Palmer Gage
	7-day Low Flow (cfs)	Annual Minimum (cfs)	7-day Low Flow (cfs)	Annual Minimum (cfs)
Actual	249	242	118	114
Natural	268	225	144	112
With HHD/without Tacoma Diversion	278	---	134	---

In 1980, the WDOE (Chapter 173-509 WAC) established instream flow restrictions on the mainstem Green River at USGS gage stations near Auburn (12113000) and Palmer (12106700). Instream flow recommendations were developed based on a study conducted by the USGS that identified correlations between low summer flows and adult salmon and steelhead returns (Swift 1979). Required instream flows at Auburn range from 300 cfs during the late summer to 650 cfs from December 1 through June 14 (Table HYDRO-4). Instream flows at Palmer range from 150 cfs to 300 cfs (Table HYDRO-4). Tacoma's First Diversion Water Right Claim (FDWRC) of 113 cfs is not constrained by these minimum instream flow requirements. However, in recent years, Tacoma has attempted to work cooperatively with resource agencies and the Muckleshoot Indian Tribe (MIT) to reduce impacts of water withdrawals on fish and other instream resources.

Table HYDRO-4: Instream Flow Requirements at the USGS gage at Auburn (USGS # 12113000) and Palmer (USGS # 12106700) under Ecology's Instream Resource Protection Program.*

Season	Auburn	Palmer
June 15 to July 14	550 cfs	150 cfs
July 15 to September 15	300 cfs	150 cfs
Sept. 16 to Sept. 30	300 cfs	150 cfs
Oct. 1 to Oct. 15	300 cfs	190 cfs
Oct. 16 to Oct. 31	350 cfs	240 cfs
Nov. 1 to Dec. 1	550 cfs	300 cfs
Dec. 1 to June 14	650 cfs	300 cfs

* These requirements may be modified during critical drought years (<1 in 10 low-flow frequency) as specified in WAC 173-509.

FLOOD CONTROL PROJECTS

Howard Hanson Dam

Prior to construction of HHD, flows as high as 28,000 cfs were measured at the Auburn gage (USGS 1996). The natural bankfull flow (approximately 2 year return interval) in the Green River at Auburn was about 12,000 cfs (Dunne and Dietrich 1978). Since construction of HHD, there has been almost a complete absence of flows above 12,000 cfs at Auburn due to flood control operations (Figure HYDRO-5), and the two-year return interval event has decreased by 24 percent, to approximately 9,100 cfs (Figure HYDRO-6). At the same time, the duration of flows between 3,500 cfs and 9,000 cfs has nearly doubled (Figure HYDRO-7).

Large floods are generally responsible for creating the diverse habitats (e.g. gravel bars, backwaters, oxbows, sloughs) associated with large alluvial rivers such as the middle Green River. The absence of large floods has had a profound influence on habitat conditions in the unconfined portion of the mainstem in the Middle Green sub-watershed, which will be discussed further in Chapter 2.3 (Hydromodification). The absence of large floods also reduces recharge of shallow alluvial aquifers that are an integral component of floodplain ecosystems (Naiman et al. 1992). During floods, water is stored in sloughs and side channels, or seeps into floodplain soils, recharging groundwater storage. This stored groundwater slowly drains back to the channel, providing a source of cool inflow during the summer (Naiman et al. 1992).

Spring refill operations at HHD have historically reduced flows for several weeks between April and June; the timing of the flow reduction is dependent on hydrologic conditions in the upper watershed and USACE operating procedures (Figure HYDRO-8). As a result, the spring flows below the dam have been lower than historical conditions prior to construction of the dam (Figures HYDRO-2 and HYDRO-3). Past refill operations at HHD have also dampened or prevented spring freshets from passing through the system in some years (Figure HYDRO-8).

Decreased spring flows and the lack of freshets have affected the availability of off-channel habitats in the Middle Green sub-watershed. In a comparison of side-channel connectivity under natural and managed conditions, Coccoli (1996) noted that the frequency of connection between side channels and the mainstem under the modeled "natural" flow regime (i.e. without HHD or

Tacoma’s diversion) was higher than under both historic or current refill strategies. The length of time that side channels are disconnected from the mainstem has also increased as a result of reservoir operations (Coccoli 1996).

Water stored behind HHD during the spring is used to augment low flows during the summer. The average 7-day low flow at the Auburn gage prior to construction of HHD was 165 cfs, compared to 248 cfs since the dam has been in operation (Figure HYDRO-9). The 7-day low flow represents the average daily flow during the seven consecutive days with the lowest flows, and is conventionally used in evaluating low flows because shorter flow durations have much greater variability.

The annual 7-day low flow based on the modeled natural flow data indicate that instream flow requirements would not have been met during low flow periods in 28 of the 32 years (87.5percent) even in the absence of HHD and Tacoma’s diversion (Figure HYDRO-9). Actual flows measured at the Auburn gage have met or exceed minimum low flow requirements in only 9 of the last 30 years. Summer flow augmentation has helped maintain summer low flows in the Middle Green River, and, in the absence of Tacoma’s diversion, would be expected to increase the average seven-day low flow by approximately 7 percent at the Auburn gage (Table HYDRO-3). Model results indicate that the average seven day low flow at Palmer has been approximately 10 cfs less than would have occurred under the natural flow regime even with flow augmentation from HHD.

Levees and Channelization

Flood control levees can also alter the hydrologic regime. Large scale levees were built beginning in the early 1900’s to help prevent the floodplains of the lower Green River from flooding (see chapter 2.3). Periodic levee construction and maintenance activities have continued to the present, both to protect higher density population areas and specific residential areas. A recent survey of the lower Green River determined that levees and stream bank revetments were present on one or both banks along approximately 5.6 miles (40percent) of the mainstem Green River between RM 32 and RM 45 (Perkins 1993). The majority of these structures are located between RM 32 and RM 37.

Channelization and confinement of the channel between levees prevent high flows from accessing the floodplains, reducing groundwater recharge. Narrow, deeper channels have higher water velocity and bed shear stress, thus even small flood events may scour of bed materials. At the same time, simplification of the channel, including elimination of access to off-channel areas, reduces the availability of high flow refugia used by salmonids to escape the high velocity flows and the stability of spawning gravel. The physical effects of levees on channel processes and aquatic habitat is discussed further in Section 5.3.

LAND USE

The primary land uses in the Middle Green River sub-watershed are agriculture and rural residential development (see Chapter 1.1). Alternation of natural vegetation communities and compaction of soils has likely altered runoff patterns in the Middle Green River sub-watershed as much or more as in the Upper Green River sub-watershed. However, there is currently no data on the effects of landuse activities on the hydrology of the mainstem Green River downstream of RM 64.5. Changes in the hydrologic regime have been identified on the major tributaries to the Green River, Soos and Newaukum Creeks, and are discussed further in the section on major tributaries.

LOWER GREEN RIVER SUB-WATERSHED (RM 11 TO RM 32)

WATER USE AND DIVERSIONS

The White River, the Cedar/Black River and the Green River formerly joined together downstream of Auburn (Figure HYDRO-10). The combined flows of these rivers, at that time called the White River, meandered freely through the extensive low gradient Duwamish Bay geologic deposits, that dominate the lower basin topography (Dunne and Dietrich 1978). The lower White River channel was quite sinuous under historic conditions. The upper White River, a glacier-fed system supplying large quantities of sediment and summer flows, joined the Green River near RM 31. The combined flow of Lake Washington and the Cedar River fed into the White River at RM 11 through a short reach known as the Black River. Flooding was frequent throughout the lower basin. Below the Black River, the river flowed through a system of tidally-influenced marshes and swamplands. Broad, intertidal flats and shallows characterized the south end of Elliott Bay.

Both the White and Cedar/Black River were diverted out of the Lower Green River sub-watershed in the early 1900s (Figure HYDRO-10), resulting in significant changes to the hydrology of the Lower Green River sub-watershed. The combined diversion of the White River and Cedar/Black Rivers reduced the drainage area of the Green River basin by almost 60 percent, with the diversion of the White having a much greater impact upon the freshwater portions of the Lower Green than the diversion of the Cedar/Black. Historically, the White River was connected to the Puyallup River via an overflow channel known as the Stuck River. The entire flow of the White River was diverted to the Puyallup River in 1906 by a log jam that formed during a flood. Because of flood control concerns, a permanent diversion structure was subsequently constructed and completed in 1911, forcing the flow of the White River to continue discharging into the lower Puyallup River.

Because it is glacially fed, the White River tends to have higher summertime flows than other non-glacial systems in Puget Sound. Diversion of the White River reduced summer flows in the Lower Green River sub-watershed by roughly 50 percent. Sediment supply to the lower basin was also reduced sharply; the impacts of this reduction will be discussed further in Chapter 2.2 (Sediment Transport) The diversions enabled salt water from the estuary to move further upstream than before.

Ground water levels in the current White River valley are significantly higher than in the Green River Valley in the vicinity of Auburn and Kent (Pacific Groundwater Group 1999). The amount of flow from the White River groundwater system to the Green River was estimated to be approximately 34 million gallons per day (53 cfs) in September 1998 (Pacific Groundwater Group 1999). Flow during wetter times of the year has not been quantified, but might be expected to be greater. The study conducted by Pacific Groundwater Group (1999) indicates that the White River is a major source of aquifers that supply water to the City of Auburn.

The Black River, which enters the Green River at RM 11, was reduced to a small fraction of its former flow in 1916 by construction of the Ship Canal/Ballard Locks and associated lowering of the water level in Lake Washington. The Cedar River, which formerly joined the Black River, emptying westward into the Green River, was diverted into the Lake Washington to provide water flows for the locks.

FLOOD CONTROL

Howard Hanson Dam

The effects of HHD operations on the Lower Green River sub-watershed are similar to those described for the Middle Green River sub-watershed.

Levees and Channelization

As described previously, large scale levees were built beginning in the early 1900's to help prevent the floodplains of the lower Green River from flooding. Perkins (1993) determined that levees and stream bank revetments affected over 80 percent of the length of channel between RM 25 and RM 31. Levees are virtually continuous along both banks downstream of RM 25 (Fuerstenberg 1996).

Channelization and confinement of the channel between levees prevent high flows from accessing the floodplains, reducing groundwater recharge. Narrow, deeper channels have higher water velocity and bed shear stress, thus even small flood events may scour of bed materials. At the same time, simplification of the channel, including elimination of access to off-channel areas, reduces the availability of high flow refugia used by salmonids to escape the high velocity flows and the stability of spawning gravel.

LAND USE

Urbanization involves conversion of land and wetlands into residential, commercial, and industrial uses. In a compilation of data from 15 previous studies, Hollis (1975) showed a pattern of increased instantaneous peak discharge with an increased percentage of impervious area. Peak flows increases of 200 to 300 percent are typical of the changes resulting from low-level suburban development (10 to 20 percent impervious area) (Booth et al. 1990). In addition, the frequency of flows capable of transporting sediment and altering the channel configuration may increase by a factor of 10 or more (Booth 1991). At the same time, since water runs off impervious surfaces rapidly, groundwater recharge typically decreases. This results in a lowering of summer flows that are sustained primarily by groundwater.

Over 60 percent of the Lower Green River sub-watershed supports Urban/Residential land uses (King County 1999). Little data is available to document flow changes in the mainstem Green River resulting from increased stormwater runoff. However, estimated peak flow increases of over 2,000percent have been identified in a number of very small tributary basins with extensive urban development (Table HYDRO-5). Primary effects of urbanization on streamflows include increased peak flows and creation of new peaks where none previously existed in association with increased impervious area and diminished summer flows as a result of reduced floodplain storage. Increased peak flows from tributary streams may exacerbate flooding in the lower Green River. Decreased tributary inflows during the summer will exacerbate low summer flows and high water temperatures in the lower Green River.

MAJOR TRIBUTARIES (SOOS AND NEWAUKUM CREEKS)

The largest tributaries to the Green River include Soos Creek, Newuakum Creek, Mill Creek and Springbrook Creek. The hydrologic regime of these major tributaries is dominated by winter rain events, with low flows occurring in the late summer (Figure HYDRO-10). The major tributaries are all located in the Middle and Lower Green River sub-watersheds, where the topography in typified by rolling hills formed on glacial deposits. Lakes and wetlands are common in the headwaters of each of these basins, and help sustain streamflows by slowly releasing groundwater during the summer months. The primary impacts on the hydrology of the major tributaries include stormwater runoff, urban development and consumptive water use.

WATER USE

Surface water rights and claims in the Soos and Newaukum Creek basins amount to approximately 27 and 10 cfs, respectively, and are predominantly for irrigation and small multiple domestic systems (Culhane et al. 1996). Groundwater withdrawals represent the largest water source in the major tributary basins. In the Middle Green River sub-watershed west of Palmer, thick glacial and alluvial deposits form aquifers with high water yields. The 1989 King County Ground Water Management Plan divides the lower and Middle Green River sub-watershed into four hydrogeologic sub-areas. These sub-areas include the Covington Upland, Des Moines Upland, Federal Way Upland, and Green River Valley (King County 1989). Water level declines have been observed in aquifers in the Covington, Des Moines, and Federal Way Upland subareas (King County 1989).

The three largest ground water supply areas in the Covington Upland are the Covington Water District Lake Sawyer Well field, King County Water District No. 111, and the Kent spring source (King County 1989). These municipal uses account for 67 percent of the groundwater rights issued in the Soos Creek Watershed. Municipal uses account for 56 percent of the total instantaneous water allocated in the Newaukum Creek basin (Culhane et al. 1996). Preliminary results from a USGS groundwater modeling study suggest that pumping even from deep aquifers in the region produces significant impacts on surface water bodies within the Green River basin (King County 1989).

Apparent declines in summer stream flow have been identified for the Soos and Newaukum basins, likely in response to increased urbanization, groundwater withdrawals and changes in precipitation (WDOE 1995). The average 7-day low flows in Soos and Newaukum Creek decreased significantly between 1968 and 1993 (Figure HYDRO-12).

LAND USE

An evaluation of the impact of future land use on basin hydrology conducted in the Soos Creek basin suggested that flood peaks could increase by an average of 180 percent over the 1985 conditions under the densest use permitted by existing or proposed land use or zoning (Table HYDRO-5)(King County 1989). The same study indicated that under existing conditions the estimated highest peak flows occur in tributary basins with the greatest development, suggesting that urbanization has already impacted flood peaks in Soos Creek. Similar impacts are believed to have occurred in the Mill Creek basin, where the amount of impervious area was predicted to increase from 20 percent in 1985 to between 45 and 70 percent by 2,000 (King County 1986). In addition to increasing the magnitude and frequency of peak flows, more rapid stormwater runoff also affects summer low flows by reducing recharge of shallow groundwater aquifers that sustain flows throughout the summer. The decreased tributary flows exacerbate high water temperatures and decrease the quality and quantity of summer rearing habitat.

Table HYDRO-5. Modeled Peak Flow Increases and Extent of Impervious Area in Small Tributaries to the Green River, Lower Green Subbasin (RM 6.5 to RM 33).

WRIA Catalog Stream #	Stream Name	Location	D.A (mi^2)	Baseline Condition	Final Condition	Peak Flow Increase (%)	Impervious Area (%)	Source
-	Riverton Creek	LB, RM 6.0	0.68	Forested	1997	256% to 2222%	88% of area developed w/residential and light industrial	Entranco et al. (1997)
-	Fostoria Creek and nearby tribs	LB, RM 6.5-12	2.5	Forested	Max. build out	0-633%	Light industrial to low density residential	KCM (1986a)
0032	Gilliam Creek	LB, RM 12.7	3.0	1986	Max. build out	0-200%[1]	High density commercial residential to low density residential	KCM (1986b)
0051	Mill Creek	LB RM 23.9	22	1985	2000	ND	Increases from 20% to 45-70%	King County (1988)
0061	Olsen Creek	RB RM 28.6	1.6	Forested	1994	33%-91%	3% (EIA)[2]	Booth (1994)
0068	Cobble Creek	RB RM 30.05	0.26	1994	ND	ND	8% (EIA) [2]	Booth (1994)
0069	Lea Hill Tributary	RB RM 30.15	0.63	1994	ND	ND	12% (EIA) [2]	Booth (1994)

[1] For 2-year event
[2] EIA=Effective Impervious Area
ND=No Data

HYDROLOGY ADDENDUM--NATURAL FLOW ANALYSIS

INTRODUCTION

The purpose of this addendum is to document a trial analysis of the nature and degree to which Green River mainstem flows have been altered by two large public works projects--Howard Hanson Dam and the City of Tacoma's flow diversion at Palmer. These flow alterations have been evaluated at Palmer (RM 61), the upstream limit of the middle Green River, in order to focus on the effects of the operation of the dam and diversion. The analysis is most conclusive for the reach between Palmer and Auburn, where the effects of the two projects are predominant. The primary goals of this analysis are twofold: principally to determine whether such an analysis is practical and feasible for assessing hydrologic impacts on Green River ecology, and secondarily to identify ecological effects of these projects where they are clear from the analysis.

This addendum presents flow data with and without the dam and diversion in place, but makes no attempt to evaluate “historic” conditions prior to the White and Cedar Rivers being diverted from the watershed, or any landuse changes as a result of logging or other land management practices. Rather, all climate and land use conditions are consistent between the two flow regime data sets.

The objective of this analysis is to evaluate changes in all major aspects of the mainstem flow regime having the potential to affect ecological processes and habitat conditions in the Green River downstream of the two projects. Given the relatively new nature of this type of analysis, results are preliminary and the methodology should be viewed as a tool that can be modified to improve its relevance to evaluation of Green River ecology.

In the future, similar analytical techniques could be applied to other portions of the watershed. In addition, this technique could be developed into a flow management strategy resulting in managed flows that more closely resemble the natural flow patterns occurring in an unregulated river.

BACKGROUND

Recent ecological research, including guidance from the National Research Council, the National Marine Fisheries Service, and others, has indicated that all aspects of the flow regime have relevance for habitat protection (e.g. NRC, 1992; Poff, et. al., 1997). This view is summarized in the following statement from a report prepared for NMFS and the US Fish and Wildlife Service: “Protection of salmonid habitats requires stream flows to fluctuate within the natural range of flows for the given location and season” (Spence, et. al., 1996).

This is in direct contrast to current legal requirements in the State of Washington, which rely on establishment of minimum instream flows as the sole flow-related requirement for fish habitat protection. This research suggests that salmonids evolved with life histories reliant on the entire range of flow variation in a naturally flowing river: the magnitude, frequency, timing, duration, and rates of change of various flow events, annual maxima and minima, etc. The research further suggests that all of these aspects of the flow regime should be evaluated in examining hydrologic factors of decline for salmon production in the Pacific Northwest.

The impacts of hydrologic change can only be fully understood in concert with other factors of decline work. Changes in hydrologic parameters become more or less important depending on ecological and geomorphic factors such as gravel regime, wood loading and recruitment, and channel complexity within the river, the life histories of the species of interest, the degree to which various reaches have been altered by channelization and levee building, etc. Thus, these impacts will be better understood after they are integrated into the rest of the factors of decline analysis. In addition, some types of impacts that are expressed here as changes in flow rates can be more specifically quantified by integrating the flow analysis into available hydraulic modeling to assess changes in flow depths and habitat area.

The analysis presented in this addendum is based on two evaluation methodologies developed by several researchers at the Nature Conservancy to evaluate hydrologic change and to design flow management regimes to more closely mimic natural flow conditions (Richter, et. al., 1996, Richter, et. al., 1997). These methods, the Indicators of Hydrologic Alteration (IHA) and Range of Variability (RVA) approaches, were tested in a pilot analysis for the Roanoake River in Virginia. It is unknown whether these methods have as yet been applied to rivers elsewhere in the Pacific Northwest. However, the principal concept of analyzing changes in a suite of hydrologic characteristics selected to represent all major aspects of the flow regime, seems wholly appropriate for Northwest rivers. Opportunities may exist to modify the analysis to select the specific hydrologic characteristics with the most ecological importance in this region. With that in mind, the analysis described below should be viewed as a tool for evaluating hydrologic change and the results should be considered preliminary. It is hoped that ongoing dialogue between ecologists, hydrologists, and other scientists and managers working on Green River habitat conservation will improve the usefulness of this methodology.

In this analysis, a comparison of flow regimes representing both “natural” or without-projects conditions and “managed” or with-projects conditions was made using equal 32-year time spans of daily flow records. The gaging sites and time span were selected to determine the effects of the two major projects affecting the Green River flow regime: Howard Hanson Dam, which was completed in 1962 for the primary purpose of flood control, and the City of Tacoma flow diversion, which supplies municipal and industrial water and has been in operation since 1913. Howard Hanson Dam lies approximately 3.5 miles upstream of the Tacoma diversion site at RM 64.5.

The measured flow data record representing the with-projects (dams and diversion) condition is from the Palmer gage (USGS No. 12106700), which is located at RM 60.4[3], just downstream of the Tacoma diversion. This gage was selected because of its close geographic location to the Tacoma diversion and minimal tributary inflow between its location and that of the diversion. The period of record used for this analysis (1964-1995) begins immediately after completion of Howard Hanson Dam and commencement of flood control operations. The data representing “natural” or without project conditions were derived from a regression of measured inflow into the Eagle Gorge Reservoir above Howard Hanson for the same time period (CH2M-Hill, 1997). Because the record used is the entire historical data set since the dams and diversion have been in place, results reflect the entire range of operating protocols that have been used during that time frame. No attempt has been made to segment out differing operating regimes, or to modify the data to better represent the Corps’ current operating guidelines at Howard Hanson Dam (HHD).

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[3] United States Geological Survey- Water Resources Data

IHA METHODOLOGY

The IHA (Indicators of Hydrologic Alteration) method uses a suite of biologically relevant flow statistics to characterize variability of a hydrologic regime and to quantify hydrologic alterations caused by human impacts by comparing regimes with and without the impact-causing projects in place. Richter et. al. (1996, 1997) suggested using flow regimes for pre- and post-project time periods to compare statistics derived from mean daily data. For this Green River analysis, however, statistics have been computed for measured and simulated flows over the same time period. This is intended to eliminate any climate- or land use-induced variation between the two data sets, and isolate the comparison to the projects.

In both situations, the data are then processed into 32 parameters for each year for both the with- and without-project flow records. The central tendency and variation of these inter-annual series are then estimated using means and coefficients of variation. This results in 32 means and 32 coefficients of variation for each data set. Absolute and percentage differences between each pair of analogous values along with their range of variability are then used to judge shifts in both the magnitude and variability of the 32 characteristics between the with- and without projects conditions.

The 32 flow characteristics calculated for each year include monthly means (12 statistics); 1-, 3-, 7-, 30-, and 90-day minimum and maximum flows (10); Julian Date of annual minimum and maximum daily flow (2); low flow and high flow pulses and durations (4); and counts and rates of flow rises and falls (4). These groups of characteristics are summarized below in Table Hydro-Add-1. Each of these characteristics have been linked in the literature to various river ecosystem functions, examples of which are stated in the table.

Table Hydro-Add-1. IHA flow characteristics and their ecological relevance.

IHA Statistics Group	Regime Characteristics	Hydrologic Parameters	Examples of Ecological Importance
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month	Habitat availability; Downstream migration rate and survival; Water temperature; Availability of spawning habitat; Access to side channels and tributary streams.
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual maxima and minima: 1-, 3-, 7-, 30-, and 90-day means	Floodplain recharge; Channel-forming flows; Sediment transport;Gravel recruitment from floodplain, gravel bars, and stream margins; Habitat availability; Wood recruitment from floodplain and stream margins; Degree of drought-induced ecological stress
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day maximum and each annual 1-day minimum	Timing of key life history stages; Timing of outmigration.
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	No. of high pulses each year; No. of low pulses each year; Mean duration of high pulses within each year; Mean duration of low pulses within each year	Impacts of dewatering and/or scouring of redds; Stranding of adult or juvenile salmonids; Connection to side channels
Group 5: Rate and frequency of water conditions change	Frequency Rate of change	Means of all positive differences between consecutive daily values; Means of all negative differences between consecutive daily values; No. of rises; No. of falls	Stress to aquatic organisms related to unusual rates or magnitudes of flow change

Adapted from Richter, et. al., 1996.

In a refinement of the original method, Richter, et. al. (1997) introduced the Range of Variability Approach (RVA) in order to facilitate application of IHA to the problem of hydrologic restoration in managed river systems. Whereas the IHA identifies the degree of change in the aforementioned indicators, the RVA goes a step further to develop ranges for natural variation of each characteristic. The authors then recommend developing flow management protocols designed to better mimic the natural regime by limiting the discrepancies between frequency distributions of natural and altered IHA parameters.

The RVA concept defines a target envelope for annual values of each of the 32 characteristics based on without-project statistics. Adequacy of the with-project hydrologic regime is then evaluated as a percentage of years for which annual values of each characteristic fall outside the defined range. Richter et. al. (1996, 1997) referred to this percentage as the “Rate of Non-Attainment,” as it used to determine to what degree the project is attaining its goals based on the RVA range. For this application on the Green River, this range will be referred to as the “Range of Typical Values;” that is the range of values that would be expected based on natural flow conditions. Richter et al (1997) does not suggest a method for identifying the appropriate range, and states that the range need not be consistent among the 32 flow characteristics. The implicit suggestion is that appropriate ranges for each variable are best selected based on the variable’s influence on biological processes. Selection of appropriate ranges may be iterative and can likely be improved with further analysis.

Absent biological information to aid in prescribing the typical range, Richter, et al. recommends use of a range spanning 2 standard deviations--one on either side of the pre-impact mean (Richter et. al. 1997). Departures of the managed flow regime from the natural regime are then described by the percentage of years that the 32 characteristics fall outside the typical range. The Roanoke River is again used as an example using this default method of establishing variability ranges. No explicit guidance is given on what is an acceptable level limit in the number of values falling outside of the defined typical range. Similarly, no direction is given to check without-project non-attainment as a standard to judge with-project non-attainment by. In the case of the default definition of range, one might be led to believe that pre-project non-attainment is 32 percent, the case for data with a normal distribution. Normally distributed flow data would result in 68 percent of all values falling within the two standard deviation range (i.e. RTV), and 32 percent falling outside.

However, flow data are often not normally distributed, and frequently have no obvious underlying distribution. In cases where no obvious distribution exists, a common statistical procedure is to rely on non-parametric methods for further analysis. This involves ranking data and relying on medians and percentiles as descriptive measures rather than means and standard deviations. While this is a departure from the method described in Richter, et. al. (1996), it is valid based on standard statistical and hydrologic texts (e.g., Maidment, 1992). In this connection, any non-parametric range can be selected for comparison. Without biological information to suggest otherwise, the 16th and 84th percentile levels have been selected given their equivalency to a two-standard deviation range for normally distributed data. Comparison using this range provides a starting point for evaluating differences between with- and without-project flows. The ranges can later be adjusted as additional information becomes available regarding the effects of each of these flow characteristics on specific biological processes and functions in the Green River.

The analysis reported in this addendum relies exclusively on non-parametric methods. Methods using normal distributions as in the literature were found not to be statistically valid for many of the data sets. In a further refinement of this work, consideration should be given to reevaluating the appropriateness of a parametric approach to analyzing these data, perhaps using log-normal or some other distribution (the best distribution may differ by hydrologic parameter).

The use of the 16th and 84th percentiles for a variability range suggests that, by definition, 32 percent of the values for each parameter in the without-project data set will fall outside of the typical range. Changes in the number of values falling outside of this range for the with-project condition can thus be used to evaluate the degree of alteration resulting from the projects.

TRIAL APPLICATION OF IHA/ RVA TO THE GREEN RIVER AT PALMER

GENERATED “NATURAL” (WITHOUT-PROJECTS) FLOWS[4]

Natural flows were developed using an unpublished computer model developed by CH2M-Hill for the Corps of Engineers’ Additional Water Storage project DEIS (CH2M-Hill, 1997). Natural flows (without projects) were derived from measured stage elevation changes at HHD. Given an estimate of the storage capacity for a range of water surface elevations and a rate of change, inflow rates were developed. These types of relationships are typically called rating curves. This

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[4] Natural flows generated by CH2M-Hill

method does have some drawbacks. If the rate of change in the inflow in any given day is significant enough, the estimated reduction in the inflow rate may be greater than the actual outflow from HHD, resulting in a negative computed flow rate. Obviously, this does not occur. To remove computed negative flow rates, they were first zeroed out, and then a smoothing function was applied. The smoothing function artificially reduces the value of extreme high flow events and increases computed extreme low flows. In contrast, using measured daily mean flow rates, the smoothing function is already partially done by representing flows that vary over the course of a day as an average flow rate. The smoothing function most adversely affects statistics associated with extreme single day values, thus 1-day annual maxima and minima were not used in this analysis. No attempt has been made to quantify this error, only to recognize it and limit the application of statistics as previously mentioned.

To account for the runoff that occurs between HHD and the Palmer USGS gage, a regression on the inflow to HHD and measured flows at Palmer for the period of record prior to HHD construction determined that "natural" flows at Palmer are typically equal to HHD inflows plus three percent. Thus, the without-project flows as computed (for the without-project data set) are equal to the measured inflows plus 3 percent for each daily mean.

With some slight variations to the IHA methodology, medians and Ranges of Typical Values were used for each hydrologic characteristic instead of means and standard deviations. The Ranges of Typical Values (referred to as RTV) falls between the upper 84th percentile and the lower 16th percentile threshold for each data set, which is consistent with the RVA methodology. The percentage of values falling within, or outside of these two thresholds, quantifies the magnitude of dispersion for a given data set. As with the RVA methodology, the number of data points above or below these thresholds are quantified. Distribution shifts between with- and without- projects conditions can then be identified based on the percentage of points falling in the upper (> 84th percentile), middle (between the 16th and 84th percentiles), and lower (<16th percentile) ranges. The RTV is defined as the middle range.

The overall degree of hydrologic change for a given characteristic is evaluated based on the change in the median value and the shift in the distribution as defined above. In order to evaluate the significance of this hydrologic change for a given characteristic, it proved useful to develop a consistent approach. This analysis in this paper uses an algorithm that can be critiqued and/or improved upon with future applications of this technique.

The approach used for this paper is as follows. A dual matrix is developed and used to convert the changes in median and distribution to a single number identified as the "Index of Hydrologic Change". This provides a cumulative qualitative descriptor for all the various aspects of hydrologic change per element of the RTV methodology. To illustrate the process for categorizing a given set of changes in the median and distribution, an example of the method is illustrated in the figure below.

EXAMPLE: ESTIMATING THE INDEX OF HYDROLOGIC CHANGE

For this example, the index of hydrologic change is determined for the September monthly means. The first step is to quantify the percent change in distributions, relative to the without-projects condition. This percent change is separately determined for each of the lower, middle, and upper ranges, defined by less than the 16th percentile, between the 16th and 84th percentile, and greater than the 84th percentile, respectively. For the September monthly mean Group 1 statistic, the percent change in the middle range of distribution is 18 percent (whether the frequency increases or decreases within a given range is irrelevant for this calculation; the absolute value of the percentage change is used). The upper range shows zero percent change, the lower range shows an 80 percent increase in frequency. Referring to the left-hand matrix in Figure Hydro-Add-1 identified as Significance of Change in Distribution, the middle range changed greater than 15 percent and the lower changed greater than 30 percent. As a result, the significance of change in the distribution in September monthly means is considered "high."

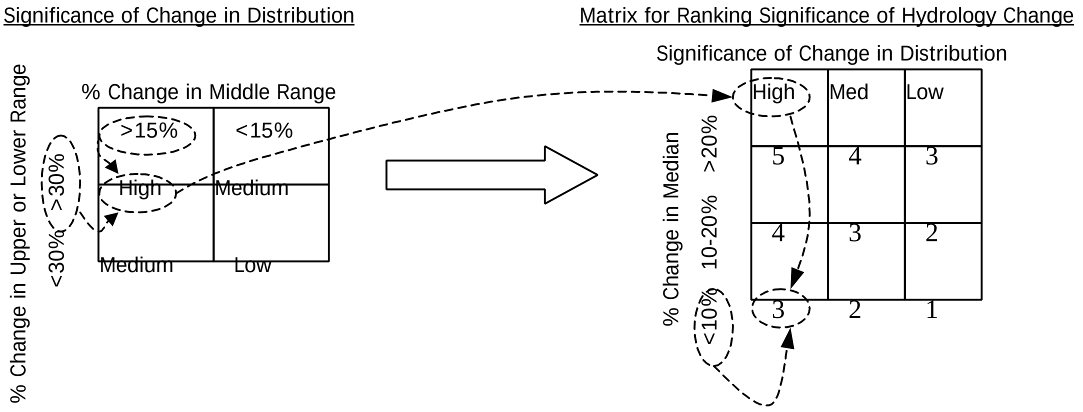


Figure Hydro-Add-1. Example for Identifying Index of Hydrologic Change.

The next step is to take that result and cross-reference it with the quantified percent change in the median value of September monthly means. For September, the median of monthly means decreased 6 percent. With these two factors of change, an index of hydrologic change value of 3 is used to characterize the overall change between without- and with-projects conditions. This index seems appropriate given that the shift in distribution is substantial while the shift in medians is slight at 6 percent. Thus, a moderate level of change is indicated.

Tables Hydro-Add-2 (which summarizes the difference between the with- and without-projects data) and 3 (which presents the specific results for the with- and without- projects data sets) represent the "IHA Report Cards." These include the calculated statistical information--medians, 16th and 84th percentiles, etc.--that were used for comparisons. The remainder of the text refers to values that can be found in those tables.

ANALYSIS RESULTS

Monthly Mean Flows

The median flows for the monthly means from each data set show that the monthly flow regime of the river has shifted substantially in about half the months of the year. Most of the change is concentrated in the spring and summer months of May through August. This shift suggests only that the distribution of monthly means without and with projects has changed substantially, but gives little indication of how that change has occurred. To determine the nature of the change that has occurred, it is instructive to compare extremes, cumulative distributions of the monthly means, and the annual values of the IHA flow parameters.

Fall and Winter (October through February)

The median of the monthly means for October increases from 362 cfs to 420 cfs, or by 16 percent, when comparing with- to without-projects conditions. This suggests that HHD has successfully been augmenting low flows and/or releasing excess stored water at the beginning of the flood season. The magnitude of the Range of Typical Values (RTV) increased by 13 percent, indicating greater interannual variability than under natural (without-projects) conditions. November has only a slight increase in monthly flow rates with a 2 percent increase in the median (from 956 to 979 cfs).

The rest of the fall and winter months show a slight decrease (1 percent - 7 percent) in monthly means with medians ranging between 1073 and 1558 cfs for with-project conditions, and from 1124 to 1574 for without-project flows.

The magnitude of the RTV increases moderately (2 percent - 19 percent) for these months with December having the largest increase with 19 percent. This is associated with an increase in the dispersion of the flows at both ends of the range and not just a shift in one direction. The distribution of flows within both the upper and lower bounds increases by 20 percent. (see columns 6 and 8 in Table Hydro-Add-2). The presumption is that HHD operations may be slightly more variable in moderating the early winter storm events, which may include rain-on-snow events. It is somewhat surprising that this moderation would show up in the monthly means comparison, since the overall flood volume for a given event is not moderated, just the peak flow and timing. It is conceivable that with a longer time period of data and current reservoir operations information factored into the analysis, this increase in dispersion would be reduced. Even with all of these shifts in median and distribution, the Index of Hydrologic Change is not greater than 2 (on a scale of 1 to 5, with 5 representing the greatest change) for the fall and winter months (see Table Hydro-Add-2 column 9, “Index of Hydrologic Change”).

The degree of the impact of Tacoma’s flow diversion on fall and winter monthly means is somewhat unclear. It appears that the amount of water diverted from the Green River was far less than 113 cfs over large portions of the record, as the average flowrate throughout the entire record is only 82 cfs (55 mgd) less for the with-project condition than without the projects in place. This is based on an application of the continuity equation, weighting the average monthly differences by the numbers of days in each month.. This reduction in flow rate is less than 10 percent of the mean winter flow; however, it is proportionally higher in October and November.

The annual distribution of monthly means during this period has not shifted substantially, but a trend in the shifts is apparent (see Table Hydro-Add-2, columns 6 – 8) with either the distribution remaining similar to without-projects conditions or shifting into the lower range of flows (below the 16th percentile).

TABLE Hydro-Add-2. Summary of Changes in With-projects Flow Conditions Data Relative to Without- Projects Conditions.

Upper Green River IHA, RVA Statistical Analyses		Summary of Change relative to Natural (without HHD or TPU)				Change in # of Excursions	Shifts in Distribution relative to Natural Conditions			Index of Hydrologic Change
		Median Difference		Change in RTV Range						
Group 1:	Monthly Means	(cfs)	%	(cfs)	%	%Difference	Lower	Middle	Upper	5= High 1= Low
	January	-16	-1%	133	6%	20%	20%	-9%	20%	1
	February	-55	-4%	41	2%	0%	0%	0%	0%	1
	March	-46	-4%	24	3%	-10%	40%	5%	-60%	2
	April	-151	-10%	58	6%	20%	60%	-9%	-20%	2
	May	-316	-23%	333	24%	40%	100%	-18%	-20%	5
	June	-222	-28%	-121	-12%	60%	180%	-27%	-60%	5
	July	-93	-30%	0	0%	110%	240%	-50%	-20%	5
	August	-51	-27%	18	14%	130%	340%	-59%	-80%	5
	September	-13	-6%	30	12%	40%	80%	-18%	0%	3
	October	58	16%	74	13%	10%	20%	-5%	0%	2
	November	23	2%	180	12%	10%	20%	-5%	0%	1
	December	-101	-7%	267	19%	20%	20%	-9%	20%	1
Group 2:	N-Day Annual Extremes	(cfs)	%	(cfs)	%	%Diff	Lower	Middle	Upper	5= High 1= Low
	1-Day Min^	4	3%	-42	-49%	-40%	-40%	19%	-40%	3
	3-Day Min	-16	-12%	-33	-43%	-60%	-20%	29%	-100%	4
	7-Day Min	-16	-12%	-28	-36%	-10%	80%	5%	-100%	3
	30-Day Min	-30	-19%	-7	-8%	80%	220%	-38%	-60%	4
	90-Day Min	-30	-15%	-3	-2%	70%	180%	-33%	-40%	4
	1-Day Max^	-848	-10%	-7512	-68%	-70%	-40%	33%	-100%	3
	3-Day Max	-284	-4%	-3772	-49%	-80%	-60%	38%	-100%	3
	7-Day Max	-33	-1%	-357	-8%	-10%	20%	5%	-40%	2
	30-Day Max	17	1%	-95	-4%	-20%	-20%	10%	-20%	1
	90-Day Max	-64	-4%	100	12%	30%	80%	-14%	-20%	2
Group 3:		days	%	days	%	%Diff	Lower	Middle	Upper	5= High 1= Low
	Julian Date of Annual Minimum	-20	-8%	8	19%	73%	220%	-38%	-50%	3
	***Julian Date of Annual Maximum**	1	1%	2	3%	30%	20%	-14%	40%	2
Group 4:		Counts or days per year	%	Counts or days per year	%	%Diff	Lower	Middle	Upper	5= High 1= Low
	Low Pulse Count	-1	-11%	2	43%	18%	20%	-10%	40%	2
	High Pulse Count	1	5%	2	40%	50%	60%	-23%	40%	3
	Low Pulse Duration (days)	9	49%	11	41%	10%	-100%	-5%	120%	4
	High Pulse Duration (days)	-1	-8%	-1	-23%	10%	100%	-5%	-80%	2
Group 5:		cfs or days	%	cfs or days	%	%Diff	Lower	Middle	Upper	5= High 1= Low
	Fall Rate (cfs)	19	12%	2	2%	-20%	-60%	9%	20%	2
	Rise Rate (cfs)	-53	-22%	-22	-12%	40%	140%	-18%	-60%	5
	Fall Count (avg per year)	-27	-12%	-10	-24%	170%	440%	-77%	-100%	4
	Rise Count (avg per year)	-9	-6%	6	32%	40%	160%	-18%	-80%	3
	Fall Count (10% Rule)	-10	-10%	-10	-25%	-29%	0%	14%	-60%	2
	Rise Count (10% Rule)	-8	-11%	0	-1%	-19%	40%	9%	-80%	3

^Values for annual extremes are not well represented as a result of the methods used to generate the natural (without HHD/TPU).

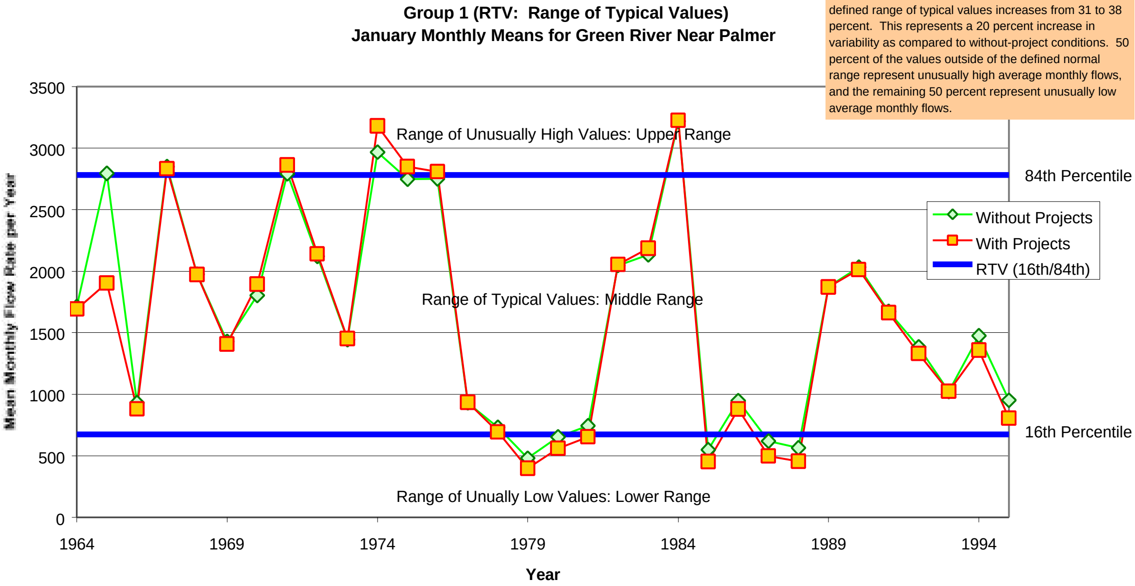
* Annual Maxima is computed on a shift of the julian date (ie. Oct 1 = julian date of 1)
Then the shift is taken out after the statistics (eg. January 1 = julian date of 1).

Table Hydro-Add-3. Summary of With- and Without-projects Flow Conditions Data.

Upper Green River IHA, RVA Statistical Analyses	Generated Natural Flow Conditions (without HHD or TPU Diversion)				Excursions Outside RTV	Measured Flows (with HHD and TPU Diversion)				Excursions Outside RTV
Group 1:	Median (cfs)	RTV Upper (cfs)	RTV Lower (cfs)	RTV (cfs)	(in percent)	Median (cfs)	RTV Upper (cfs)	RTV Lower (cfs)	RTV (cfs)	(in percent)
January	1574	2780	675	2105	31%	1558	2825	587	2238	38%
February	1250	2431	650	1781	31%	1195	2420	597	1823	31%
March	1124	1572	850	722	31%	1078	1516	771	745	28%
April	1456	1969	919	1050	31%	1305	1950	841	1108	38%
May	1389	2263	902	1361	31%	1073	2207	513	1694	44%
June	785	1446	454	993	31%	563	1092	220	872	50%
July	312	617	232	385	31%	219	537	151	385	66%
August	189	286	162	124	31%	138	260	119	141	72%
September	204	402	142	260	31%	192	411	121	290	44%
October	362	773	193	580	31%	420	804	149	654	34%
November	956	1946	474	1472	31%	979	2063	411	1652	34%
December	1446	2217	821	1396	31%	1345	2421	758	1663	38%
Group 2:										
1-Day Min	115	152	68	85	31%	119	141	98	43	19%
3-Day Min	134	174	99	76	31%	119	142	99	43	13%
7-Day Min	136	186	109	77	31%	120	151	102	50	28%
30-Day Min	158	212	130	82	31%	129	183	107	76	56%
90-Day Min	199	289	163	126	31%	170	258	135	123	53%
1-Day Max	8573	16089	5038	11051	31%	7725	9375	5836	3539	9%
3-Day Max	6806	11973	4243	7730	31%	6522	8599	4642	3958	6%
7-Day Max	5102	8017	3403	4613	31%	5069	7437	3181	4256	28%
30-Day Max	2569	4213	1975	2238	31%	2587	4163	2021	2143	25%
90-Day Max	1753	2282	1428	854	31%	1689	2266	1312	954	41%
Group 3:										
Julian Date of Annual Minimum	261	284	240	44.3	34%	241	275	222	53	59%
***Julian Date of Annual Maximum**	99	122	62	60.9	31%	99	124	61	63	41%
Group 4:										
Low Pulse Count	4.5	7.0	3.0	4.0	34%	4.0	7.7	2.0	6	41%
High Pulse Count	10.5	14.0	9.0	5.0	31%	11.0	14.0	7.0	7	47%
Low Pulse Duration	18.0	36.0	10.0	26.0	31%	26.8	52.0	15.4	37	34%
High Pulse Duration	7.8	11.4	5.9	5.6	31%	7.1	9.5	5.2	4	34%
Group 5:										
Fall Rate	158	223	99	124	31%	177	256	130	126	25%
Rise Rate	238	353	171	182	31%	185	297	137	160	44%
Fall Count	215	244	203	41	31%	188	204	173	31	84%
Rise Count	131	138	120	18	31%	123	136	112	24	44%
Fall Count (10% Rule)	91	105	67	38	31%	82	96	67	29	22%
Rise Count(10% Rule)	72	82	53	30	31%	64	77	47	29	25%

* Annual Maxima is computed on a shift of the julian date (ie. Oct 1 = julian date of 1)
Then the shift is taken out after the statistics. Thus anything over 365 means January, February, etc.

An example for quantifying distribution changes for the January monthly mean flow rates is shown below in Figure Hydro-Add-2 and in the text below. The number of annual January monthly mean flow rates that fall outside of the defined range of typical values (the RTV) increases by 20 percent under the with-project scenario. However, both with- and without-projects monthly means are evenly distributed above and below RTV limits, with 50 percent of the extreme values occurring above the 84th percentile threshold and 50 percent of the extreme values occurring below the 16th percentile threshold. Furthermore, the magnitude of the RTV increases 6 percent (see Table Hydro-Add-2, column 4) which constitutes only a mild increase in variability. The Index of Hydrologic Change based on these results is valued at 1, the lowest level. All of this together suggests that HHD and Tacoma Public Utilities (TPU) diversion operations have caused only minor changes to January monthly means. Similar and even less significant are the changes in the February monthly means (see Table Hydro-Add-2)


Example of obtaining Non-attainment based on RTV
Group 1 (RTV: Range of Typical Values)
January Monthly Means for Green River Near Palmer

The proportion of mean monthly flows outside of the defined range of typical values increases from 31 to 38 percent. This represents a 20 percent increase in variability as compared to without-project conditions. 50 percent of the values outside of the defined normal range represent unusually high average monthly flows, and the remaining 50 percent represent unusually low average monthly flows.

Figure Hydro-Add-2. Example of determining distribution of flows outside the range of typical values for January Monthly Mean flow rates. Note the defined range of typical values is based on the 16th and 84th percentile thresholds of the "without-project" mean flows.

Spring and Summer (March through September)

March shows a 10 percent decrease in the number of unusually high or low mean monthly flows. However, the distribution of the monthly mean flows is much more descriptive. There is a 60 percent decrease in unusually high flows (above the 84th percentile value of 1572 cfs), while there is a 40 percent increase in unusually low flows (below the 16th percentile value of 850 cfs), and a 5 percent increase in typical flows falling between these values. It appears that HHD is reducing the extremes, and shifting the distribution to lower flows. Again, the TPU diversion no doubt plays a role in this net reduction as does the operations of the HHD capturing water summer low flow augmentations. Effects on April monthly means are similar except for a slightly greater shift in the distributions to the lower range of values below the 16th percentile (see Table Hydro-Add-2). Overall the changes in the early spring hydrology are considered to be rather minor with an Index of Hydrologic Change of 2 for both months.

For the months of May and June, the analysis consistently shows that the river flows more often at "unusually" low levels. The median of the monthly mean flows has decreased by 23 percent and 28 percent respectively as compared to the without-project scenario. For May, the number of data points less than 902 cfs (the 16th percentile threshold for May) increases by nearly a factor of 2 from 16 percent to 31 percent of the time. Similarly, June "low" flows (less than 454 cfs) occur in 38 percent instead of 16 percent of the years (see Table Hydro-Add-2). The magnitude of the shifts in distributions and the reduction in the monthly means results in an Index of Hydrologic Change of 5. This is likely due to the combined effect of Tacoma's direct water withdrawal from the river and of these months historically being the heart of the Corps' spring refill period for Howard Hanson Reservoir, so that much of the melting snowpack and springtime precipitation was being stored for later release during the summertime. Springtime refill has occurred earlier in more recent years, so that these results might differ if the current operating guidelines were fully analyzed in place of the historic record.

The entire flow distribution is dramatically shifted downward in July and August, with median flows decreasing by 27 percent and 30 percent, respectively. For August, this shift results in a median measured flow value of 138 cfs. Consequently, excursions outside the RTV for May through August have increased by factors ranging from 2.1 to 2.3. The distribution of monthly means shifts from the assumed 16 percent above, 16 percent below the RTV range (which occurs for without-project flows) to 3 percent exceedance above and 69 percent exceedance below the RTV. So under the with-projects scenario, 96 percent of the values outside the RTV are in the low distribution band for the month of August. Similarly, the June and July distributions of excursions are 88 percent and 81 percent in the "low" distribution band.

More specifically, simulated "natural" conditions show that 44 percent of the mean monthly July flows occur between 250 and 350 cfs. This distribution shifts downward by 100 cfs, with 47 percent of the flows occurring between 150 and 250 cfs for with-project conditions. Similarly in August, 69 percent of the flows occur between 200 and 300 cfs for simulated without-project conditions. With- project flows for the same time period show 60 percent of the flows are now between 150 and 200 cfs. This shift coincides with typical magnitudes of the TPU diversion, thus suggesting the conclusion that the diversion is responsible for this distribution shift, and that HHD does not successfully augment flows to overcome the diversion impacts. Given the magnitude of these changes the Index of Hydrologic Change is 5.

September flows appear to be moderately influenced by the projects. There is an estimated 40 percent increase in the number of unusually high or low flows. Two-thirds of those unusual flows fall below the low flow threshold of 142 cfs, suggesting that the distribution has shifted toward lower flows (see Table Hydro-Add-2). These moderate shifts result in an Index of Hydrologic Change of 3.

Extreme Lows and Highs

The second section of Tables HydroAdd-2 and 3 demonstrate IHA results for the interannual distributions of annual extremes over a range of durations. The standard IHA approach of focusing simply on the increase in the number of values outside the RTV would suggest that changes to flow extremes resulting from the projects are minor. However, this is deceiving, because it does not account for the potential impact on less frequent events, which may play an important ecological function. Sample medians of the 3-, 7-, 30-, and 90-day minima have decreased by between 12 and 19 percent from the without-projects condition. The 3-day minima, for example, is 134 cfs for without- projects conditions vs. 119 cfs with the projects in place.

The upper tail of the without- projects flow distribution has been consistently and substantially truncated. For example, 47 percent of the 3-day annual minima under “natural” conditions would have been between 80 cfs and 140 cfs. With the combined operational impacts of HHD/TPU, 78 percent of all occurrences are within this range (see Figure Hydro-Add-3. Distribution of Mean 3-Day Annual Minima (1964-1995). Similar changes have occurred to the 7-day minimum flows. Longer duration minima are statistically quite similar between the two samples. In fact, there appears to be a trend with the durations. For short duration minima, the with-project flows have a tight distribution. As the duration increases, the with-projects regime transitions to a distribution that is more similar to without-projects flows but with a shift toward lower overall flow rates. In general, even with the specific low flow augmentation objective of Howard Hanson Dam, it appears that the effects of the TPU diversion were not fully offset by Dam operations. The potential for unusually low short-duration flows during dry years still exists. It appears springtime storage for conservation did not fully make up for the diversion’s impacts in these drought years.

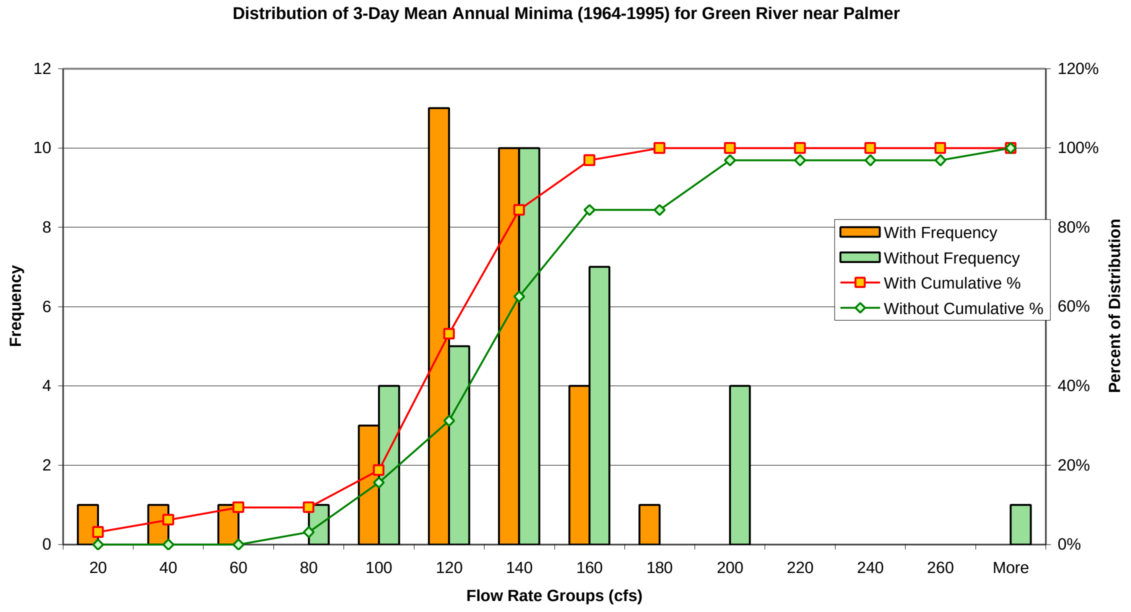


Figure Hydro-Add-3. Distribution of Mean 3-Day Annual Minima (1964-1995) for the Green River near Palmer

The comparison of the distributions of annual maxima for the without-project and with-project scenarios shows far more contrast than the minima. This arises from the obvious impact that HHD has had in suppressing flood discharges and is most evident for the shorter duration maxima. Comparing 3-day maxima, 16 percent of natural (without HHD/TPU) 3-day maxima exceeded 11,000 cfs while there are no incidences of these large flows with HHD and the TPU diversion in place (see Figure Hydro-Add-4 Green River near Palmer 3-Day Annual Maxima from 1964-1995)The difference between the without-project and with-project samples declines quickly as the duration of the maxima increases.

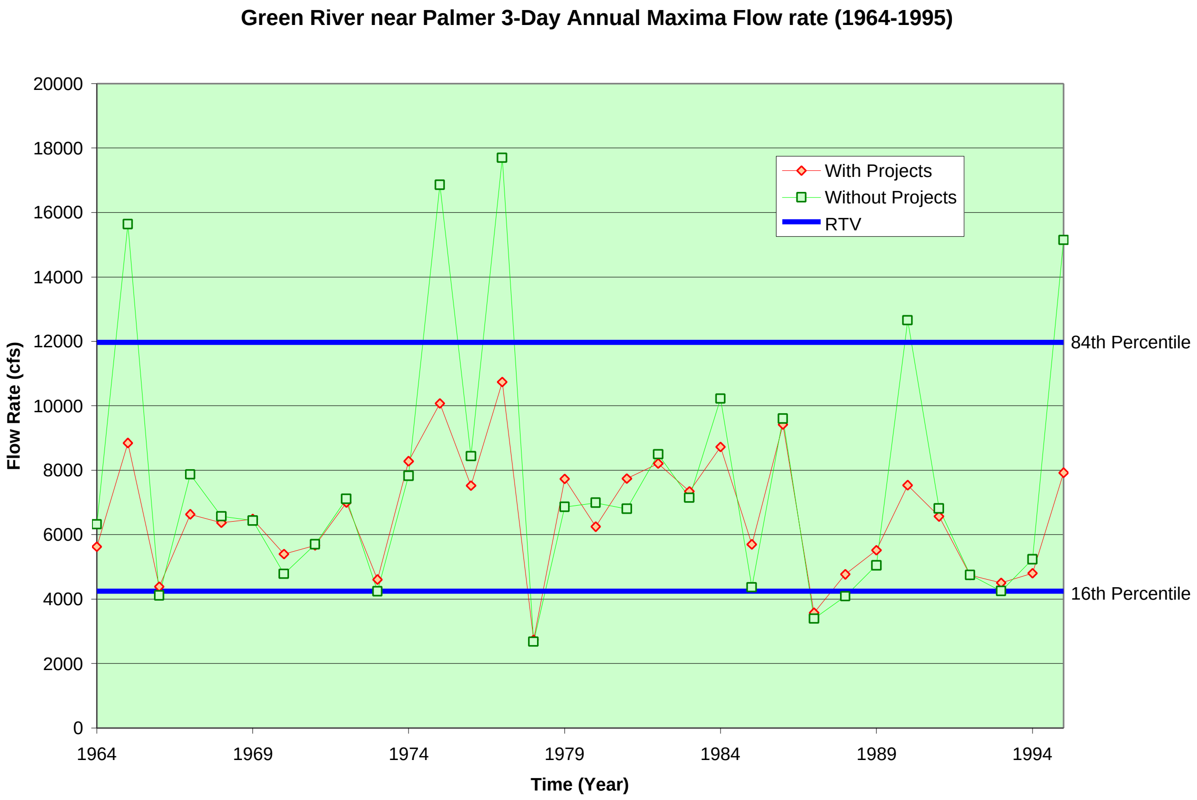


Figure Hydro-Add-4 Green River near Palmer 3-Day Annual Maxima from 1964 to 1995

The Index of Hydrologic Change varies from 1 to 3 for the maxima comparisons, with moderate (level 3) change occurring in the 3-day flows. Given the extreme moderation of short-duration flood flows due to HHD operations, this index may understate the significance of the change in this instance.

Timing of Annual Extremes

The IHA method calls for calculation of statistics based on Julian dates of annual extremes. The Julian date is calculated sequentially from the first day of the calendar year, which takes on a Julian value of 1. For hydrologic regimes where the date of annual extreme values straddles the New Year, the use of Julian dates produces unreasonable statistics. For this reason, this analysis used October 1, the first day of the hydrologic water year, as the first day of the year for computing timing of maxima. The results have then been converted back to calendar dates for discussion purposes. Although the validity of the magnitude of the 1-day annual maxima and minima is uncertain, the timing of the 3-day and 1-day annual maxima and minima are the same. Hence, discussions in this section will refer to annual extremes of unspecified duration.

Under without-projects conditions, the annual minimum flow typically occurred during the third week of September (the median value). In approximately 2 out of 3 years, the minimum daily flow occurred in a 44-day period between August 28 and October 11. In the measured (with-projects) flow sample, the median date shifts earlier in the year by about 3 weeks and the date range for 2 out of 3 years lengthens to about 53 days--starting on about August 10 and ending October 2. In the with-projects flow regime, the minimum flow is typically earlier, but also more variable in its timing. The driving factor behind this shift in the flow regime is unclear.

As discussed earlier, three-day maximum flows have been greatly reduced by HHD operations. These lower maximum flows tend to occur on the same date under with- and without-projects conditions with a median date of January 2. The variability of the annual maximum flows has increased only slightly and is considered to be negligible. Two-thirds of annual maximum daily flows would have occurred between December 1 and January 30 without the projects in place. With the projects, two-thirds occur between November 30 and February 1. These differences in timing are very small in comparison to the change in magnitude of annual maximum daily flows discussed earlier.

Frequency and Duration of Low and High Flow Pulses

In this section a low flow pulse is defined as a decline in daily discharge below the 75 percent exceedance level and conversely, a high flow pulse is a rise above the 25 percent exceedance level. For the Green River near Palmer, the daily mean flow thresholds at the respective exceedance levels are approximately 302 and 1292 cfs. This category includes 4 annual parameters: the number of high pulses, the number of low pulses, and the mean duration of each type of pulse. Of these four statistics, the low pulse durations in particular appear to have changed substantially, with an increase of 49 percent in the median duration of flows below the low flow threshold compared with natural (without-projects) conditions. High pulse counts and durations are not well represented using the 25 percent exceedance level, which is simply set too low to have much ecological relevance. To better elucidate the high pulse counts and durations, a 1 percent exceedance level (5925 cfs) could be used as a better descriptor.

Low Pulse Counts, Low Pulse Durations, and Total Annual Low Flow Days

The average number of low pulses under the with-project scenario decreased from around 4.5 per year to 4.0 per year as compared to the without-project scenario. In this case, the RVA analysis may not be completely suitable. The annual data are integer values within too narrow a range to be considered approximately continuous. Given the change in median values from 4.5 to 4.0, it would appear that the annual incidence of low flow pulses has not decreased significantly. However, low flow durations do change substantially. On average the low flow pulse increases in duration by 9 days. This is a 49 percent increase over without-project conditions. This again is likely an effect of the TPU flow diversion not being completely overcome by Howard Hanson Dam flow augmentation.

Although it is not included on the standard IHA “report card”, another useful statistical parameter may be the total number of annual days of low flows, which is simply the product of the average annual low pulse count and the average low pulse duration. On average, there are 49 percent more days per year with flows of less than 302 cfs, the low flow pulse threshold. Additionally, a comparison of the cumulative distributions for these two data sets shows that the 84 percent exceedance value for the number of annual low flow days (107 days per year) has become a 97 percent exceedance for the HHD/TPU sample. Furthermore, the 16 percent exceedance under without-projects flows (40.4 days) increases to 38 percent exceedance. In other words, there are over twice as many years where low flows persist for more than 40.4 days.

High Pulse Counts, High Pulse Durations, and Total Annual High Flow Days

Neither comparison of medians nor comparison of distribution ranges suggests much change in the number of annual flow excursions above 1292 cfs (the 25 percent exceedance daily mean under without-project conditions). This recommended IHA threshold does not appear to have much ecological relevance in that most of the ecological functions associated with high flows—scouring of bed materials, floodplain recharge, creation of new channel forms, etc.—are associated with flood events rather than routine moderate high flows. Thus a more stringent high flow threshold might be more instructive. As for high flow pulse durations, the median and magnitude of the RTV have either stayed the same or decreased with HHD/TPU in place (see Table Hydro-Add-2, Group 4, column 4), but not substantially. The 16 percent non-exceedance threshold for average annual high pulse duration has shifted from 11.4 days to 9.5 days.

Since this parameter is described as a “high” flow threshold, one might be tempted to interpret this hydrologic change as resulting from the flood control operations at HHD. However, 1292 cfs is much smaller than a flood condition for the Green River. In fact, when using a pulse rate defined as the 1 percent exceedance level (5925 cfs), the influence of HHD operations clearly result in an increase in high flow pulse durations (over 39 percent) despite the pulse counts remaining about the same (see Table Hydro-Add-4 below). The conclusion here is that Green River flood peaks are now substantially reduced, but they persist for much longer periods of time.

The reader should note that the mean is used instead of the median for average evaluation. The median would not represent correctly the observed differences between without- and with-projects conditions given the small number of excursions.

TABLE Hydro-Add-4. **Comparison of High Pulse Counts and Durations Using the One Percent Exceedance Flow Threshold (5925 cfs).**

High Pulse Rate defined by 1 percent exceedance level (5925 cfs)								
	Without Projects High Pulse		With Projects High Pulse		Difference relative to without Projects			
	Durations	Counts	Durations	Counts	Durations	Counts	Durations	Counts
min	0	0	0	0	0	0	N/A	N/A
max	5	7	7	7	2	0	40%	0%
mean	1.6	1.7	2.3	1.6	0.6	-0.1	39%	-4%

IHA Rates and Frequencies of Change

Group 5 includes four annual statistics that measure the average number of rises and falls per year, and the magnitude of those rises and falls. Richter, et. al. (1996), did not provide any guidance on applying a threshold to determine which individual flow rises or falls are worth counting. Therefore, the detection of a rise or fall is only dependent on the precision with which the daily flow data are reported, in this case 1.0 cfs. This means that a one-day “blip” with a 1.0-cfs incremental increase in flow followed by a corresponding 1.0-cfs decrease is counted as a rise just as a similar event involving a 1,000 cfs change is counted. This results in the analysis being a simple accounting of how often river flows are in a rising versus a falling hydrograph.

With this caveat in mind, the following are the results of the IHA report card (Tables Hydro-Add-2 & 3).

Fall Rate (the average daily decrease in flow for “falls” or declining flow days)

With and without HHD/TPU influence, the basic statistics appear quite similar, yet there appears to be a distinct loss of variability in the with-project statistics. By IHA standards, there has been a mild change based on the IHA Range of Typical Values criteria. However, there has been some loss of variability with a 60 percent decrease in values above the 84th percentile, a 9 percent increase in the number of values within the RTV, an overall decrease of 20 percent in variability, and an Index of Hydrologic Change of 2.

Rise Rate (the average daily increase in flow for “rises” or rising flow days)

There appears to be a significant reduction in the rate at which Green River flows tend to rise. Under without- projects conditions, the median rise in flows per day during a rising hydrograph period is 238 cfs. With the projects in place, this has been reduced to 185 cfs.

The overall distribution shifts downward as well. The number of values falling outside the Range of Typical Values for with-projects conditions is excessive, about 40 percent more than would be expected under without-projects flow conditions, with 2.4 times as many values falling below the 16th percentile. Comparisons of the cumulative distributions basically corroborate the pattern shown by these statistics--many years exhibit much smaller average rates of rise than would have occurred without the projects in place. This suggests that the Green River has lost a certain amount of overall dynamism, a finding that would be consistent with controlled floods with the projects in place. The Index of Hydrologic Change evaluates this change to be among the most significant with an index level of 5. It is unclear what role this change plays in the factors of decline analysis for salmonid production.

Fall Count--This metric counts every 1.0 cfs or larger daily reduction in flow. The median annual fall count appears to have fallen moderately. The number of values outside of the RTV is 170 percent higher than under the without-projects regime. However, the lack of precision in the definition of this statistic (any fall or rise gets counted no matter how small) and the uncertainty of its ecological importance make the value of additional comparison and analysis questionable at this time.

Rise Count- As discussed above, the statistic is too poorly defined to make meaningful comparisons. These counts might have more meaning if a threshold were utilized. For example, rises or falls could be required to involve a change of at least 10 percent in the mean daily flow relative to the previous day in order to be counted. This requirement has been applied and analyzed as follows.

When the fall and rise count statistics are computed using a requirement of a 10 percent change in the mean daily flow relative to the previous day, the with-projects regime exhibits moderate decreases in the median number of annual falls and rises of approximately 10 percent and 11 percent, respectively. The number of falls per year decreases from 91 to 82, while the number of rises decreases from 72 to 64 per year. The counts show an overall shift downward in the number of flow changes greater than 10 percent for the statistics with the HHD/TPU projects as compared to “natural” (without projects) conditions.

The proportion of counts outside the Range of Typical Values decreases by 29 percent and 19 percent, respectively, suggesting that the number of these events per year becomes overall, less variable with the projects in place. The distribution of the counts shifts from approximately 50 percent each above and below the RTV to an 80 percent decrease in the number of counts above the 84th percentile and an increase of 9 percent in the RTV and a 40 percent increase in counts below the 16th percentile. Because of the weighting applied to the median percent change and the percent change in the RTV, the Index of Hydrologic Change is 3. These shifts again seem to indicate an overall decrease in the dynamism of the river’s flow regime.

This 10 percent rule or a similar modification, perhaps applied over the springtime data set only, appears promising in evaluation of the adequacy of freshets.

SUMMARY OF HYDROLOGIC ALTERATIONS

The most notable trend between flow conditions with and without the Howard Hanson Dam and Tacoma Public Utilities projects is the overall decrease in most median flow values. Related to this finding is the overall downward shift in flow distributions and in the percentage of unusually low values compared to the without-projects conditions. Along with this shift downward, interannual variability of monthly means tends to increase, largely because lower mean values shift down by a greater amount than higher mean values.

In contrast, the variability of many of the other parameters—minima, maxima, and fall and rise rates and counts—tends to decrease. In addition, the median rate at which river flows rise per day decreases. Taken together, this suggests an overall loss in river flow dynamism. River flows change more slowly on a day to day basis than under "natural" (without- projects) conditions, especially during rising periods, and both flood and low flows are reduced and highly moderated.

For large magnitude events (flood flows), the effects of Howard Hanson Dam are quite clear. One-day and 3-day annual maxima medians decrease substantially, as does the upper end of the distribution. Without-projects daily mean flows range from 70 to 29,000 cfs with 16 percent of annual 3-day maxima exceeding 11,000 cfs. Howard Hanson Dam operations significantly truncate the upper end of this distribution, however, no flows above 10,700 cfs have been measured at Palmer with the projects in place.

The effects of the TPU diversion are less obvious than those attributable to operation of Howard Hanson Dam. The influences of the TPU diversion appear to be noticeable only during low flow periods when the amount of water being diverted comprises a significant percentage of the river flow. Furthermore, it has not been identified whether other factors may play a part in any deviation from natural conditions resulting from the diversion. Without examining individual events and TPU operational practices, it is difficult to determine whether and to what degree the diversion influences the hydrologic regime except for the fact that reductions in monthly means are clearly at least partially attributable to the diversion. It is also clear that HHD flow augmentation does not fully overcome the flow reduction effects of the diversion during extreme low flow periods.

Table Hydro-Add-5 summarizes the results of the comparisons for each individual IHA parameter.

Ecological Implications

The areas of hydrologic change due to operation of the projects appear to have clear implications for Green River salmonid ecology. Some of these implications are highlighted below:

1. Reduction in annual minimum and summertime low flows, and increase in duration of flows below 302 cfs low flow threshold. This hydrologic impact clearly reduces spatial habitat for rearing, and reduces water depth in pools, glides, and riffles. Reduced water depth over riffles increases the difficulty and energy expenditure of upstream migrating adult salmon, particularly chinook which are migrating during the low flow period. Reduced depths also reduce the quality and quantity of pool habitat used by holding adults, particularly chinook. Reduced pool depth increases the vulnerability of juvenile salmon to some predators. Reduced flows typically reduce water velocity and thus the speed of juvenile salmon outmigration, particularly for chinook and coho. Survival of outmigrating juvenile coho increases with flows and it is thought the same applies to chinook. Low mainstem flows may also be reducing upstream adult and overall juvenile movement in the river and into tributaries and side channels, and may be resulting in a redistribution of chinook redds towards the middle of the river, where flows are deeper and more subject to scour during high flows. Chinook adult migration in particular occurs during the late summer and early fall when these effects are most pronounced. However, reduced flow volumes affect the entire suite of salmonid species. The

reduction in low flows likely also plays a role in the high temperatures the Green River experiences during this time period.

2. Timing of annual minimum flow. The earlier minimum flows may also be affecting the timing of upstream adult migration, and may be contributing to warmer, more stressful instream conditions. The period of earlier minimum flows may correspond to the period of time when many chinook are shifting from upstream migration and holding to spawning.

3. Reduction in annual maxima (flood peaks). The Green River likely has less ability to create new side channel habitat, maintain existing side channels, and recharge its floodplain. In addition, river margin habitats such as gravel bars are less dynamic environments and are stabilizing, with vegetation recolonizing gravel bars throughout the upper portions of the Middle Green River from Flaming Geyser to Whitney Bridge. Without recruitment of gravel above HHD, any flow rates above the threshold of incipient bedload motion will erode away existing gravel bars resulting in a net loss of gravel bar habitat in this same reach. Reduction of flood peaks may also reduce the recruitment of wood from the floodplain and the stream margins.

4. Changes in durations of moderate flood flows. The picture here is somewhat unclear as durations of flows above 1292 cfs have decreased slightly due to the projects, while durations above 5925 cfs have increased. River bed scour is thought to be initiated at 1000 cfs in the Palmer reach, and at 2000 cfs downstream of Flaming Geyser. However, a detailed sediment budget to integrate bed movement information with a flow duration curve has not been performed at this time.

Data Gaps

The results of the analysis suggest several data gaps where additional research into flow records and/or records of operations may improve these conclusions. Two of these are listed below:

- Howard Hanson Dam operations--The analysis of managed conditions is wholly based on the measured flows at Palmer over the period of record, even though Howard Hanson Dam operations have changed during that time period. In particular, changes in spring refill timing and flood ramping rates may have an impact on downstream hydrologic conditions. The model could be revised to clearly define HHD operating guidelines and simulate managed conditions over the entire time period as if current operations had prevailed.

- TPU flow diversion records and protocols--Review of diversion records would improve the evaluation of diversion impacts during extreme low flow periods by isolating the effects of the diversion from HHD flow augmentation operations. From a comparison of mean monthly flows for with- and without-projects conditions, it is clear that the entire 113 cfs diversion right was not always implemented.

Possible Improvements to the IHA/ RVA Methodology as Applied to the Green River

There are several areas where the methodology itself could perhaps be improved, at least for application in the Green River. Since the primary goal of this addendum is to present a methodology for describing hydrologic changes in terms that may be useful in determining ecological factors of decline, it is worth noting several aspects of the analysis that might be improved through modification.

Additionally, the specific flow characteristics chosen for the analysis may not be those with the greatest ecological relevance for the Green River. Again, characteristics were chosen based on the method as described by Richter, et. al. They are statistically based and in aggregate comprehensively describe the flow regime. However, modification of individual parameters might improve the relevance for analyzing effects on Green River ecology.

For any changes to the method to be made, they should not only improve its ecological usefulness, but also remain valid and defensible from a hydrologic and statistical point of view. Several possible modifications are listed below:

- As mentioned earlier in the report, the analysis may not accurately model low and high flow extremes. In practice, the 1- and 3-day maxima and minima results are the most suspect. This is due to the smoothing factor used in the simulation of without-project conditions. Improvements to the methodology should focus on evaluating the importance of this error, and on reducing it if necessary.

- The Richter method also recommends choosing the 25 th and 75th percentiles for high and low flow duration analysis (i.e., the computed mean duration of high flow pulses is based on all pulses above the 25 percent exceedance level in a given year). However, any flow threshold could be chosen for this analysis, including thresholds of known importance for Green River ecology. Examples might include flow thresholds known to inundate side channel connections, maximize spawning area, mobilize bed sediments, or create significant floodplain recharge. It may be worth increasing the high flow pulse rate threshold to some value or values of common importance to channel morphology and biological conditions. Note that the 25 percent exceedance pulse rate is either very near or below the mean monthly flows during the wintertime, thus providing no further insight into hydrologic alteration. The 1 percent exceedance rate used as a supplement to the original IHA suite of parameters was not *specifically* selected for its relevance in evaluating factors of decline, but clearly provides more descriptive power by focusing on values closer to the upper end of the flow range with the potential to have geomorphic importance.

- In the high and low pulse count analysis, there is no difference in the relevance of a 1 cfs and a 1,000 cfs daily fluctuation. Both trigger one “pulse count.” Further analysis using some threshold of “significant” change relative to the mean daily flow rate should be considered. The “10 percent rule” used as a supplement to the IHA method seems to improve the usefulness of this parameter.

- The mean monthly flow computations may not be a fine enough resolution to fully examine impacts on Green River salmonid life histories. Other options for consideration include comparison of two-week means, or of “rolling” or moving four-week means in which each successive overlapping four-week period is used for comparison (e.g., four week periods might begin on January 1, January 8, January 15, etc.).

- Consideration should be given to modifying the definition of the Range of Variability, currently set at +/- one standard deviation from the mean, or at the 16th and 84th percentiles. These bounds for the range are somewhat arbitrary and have no clear hydrologic significance. The non-parametric analysis appears to provide better results for most flow characteristics; under this approach, a range of flow quantiles could be used or cumulative distributions could be examined in a more rigorous way.

- Consideration should be given to improving the analysis of seasonal impacts of flow alteration. For example, relative low flows might be important for different reasons in the winter as well as the summer. Thus, a low flow analysis specific to the winter/ spring time period may be useful. Relative high flow pulses could also be important within a season, such as spring freshets. The rates of change used to define a “pulse” may require further work, and again the most useful pulse definition may differ by season (e.g., 10 cfs/ day in the summer; 100 cfs/ day in the winter).

- The concept of reducing this analysis to a simple metric such as the Index of Hydrologic Change should be explored further. This idea, which was developed specifically for this addendum, appears to have promise for evaluating the significance of the various aspects of flow change. In its current rendition, however, it may not fully account for certain types of impacts. For example, the 3-day annual maxima index value is 3, which may understate the impacts of flood control on annual peaks.

- The use of statistical validation methods and application of confidence limits should be considered.

Figure Hydro-2. **Average monthly flows at USGS gage 12106500 near Palmer before construction of Howard Hanson Dam, and at USGS gage 12106700 near Palmer after construction of Howard Hanson Dam. Gages were installed at slightly different locations, but had similar drainage areas (230 and 231 sq. mi, respectively).**

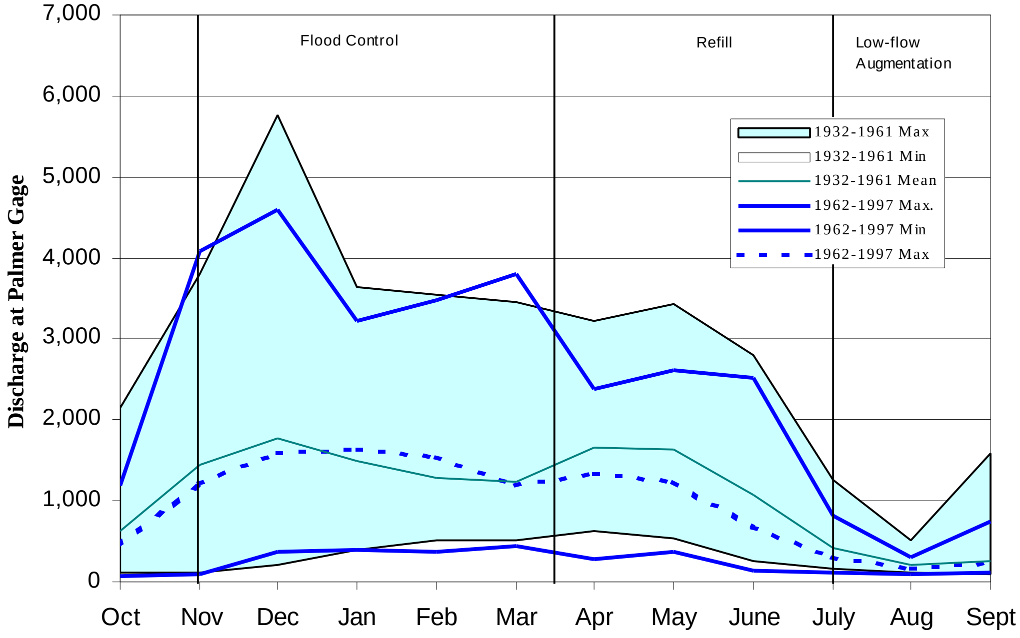


Figure Hydro-3. Average monthly flows at USGS Gage 12113000 at Auburn, before and after construction of Howard Hanson Dam.

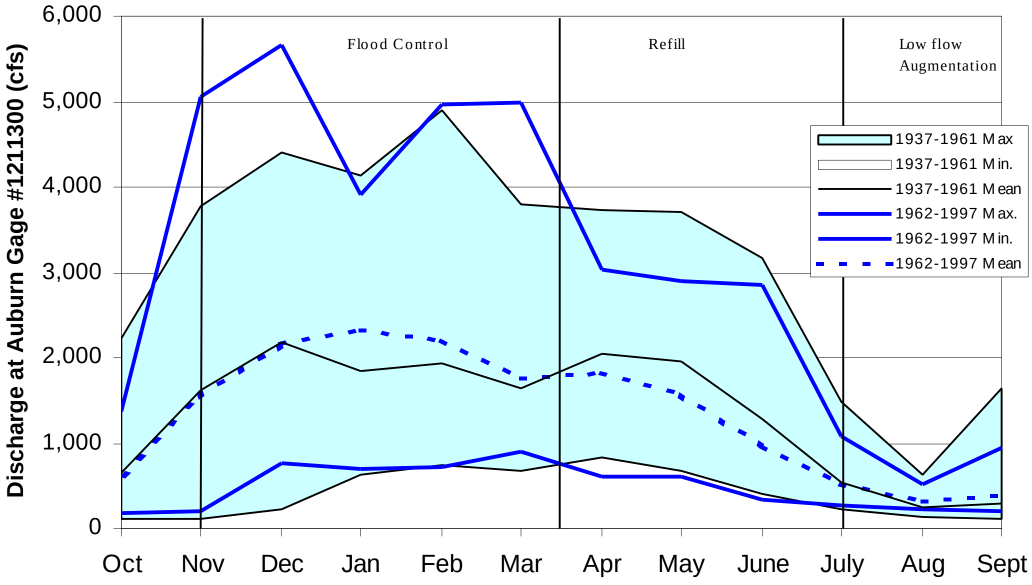


Figure Hydro-4. Green River Watershed surface water rights: primary purpose of use as a percentage of total allocated, out of a total allocated quantity of 195.2 cfs (Culhane 1995; Tacoma Water 1999).

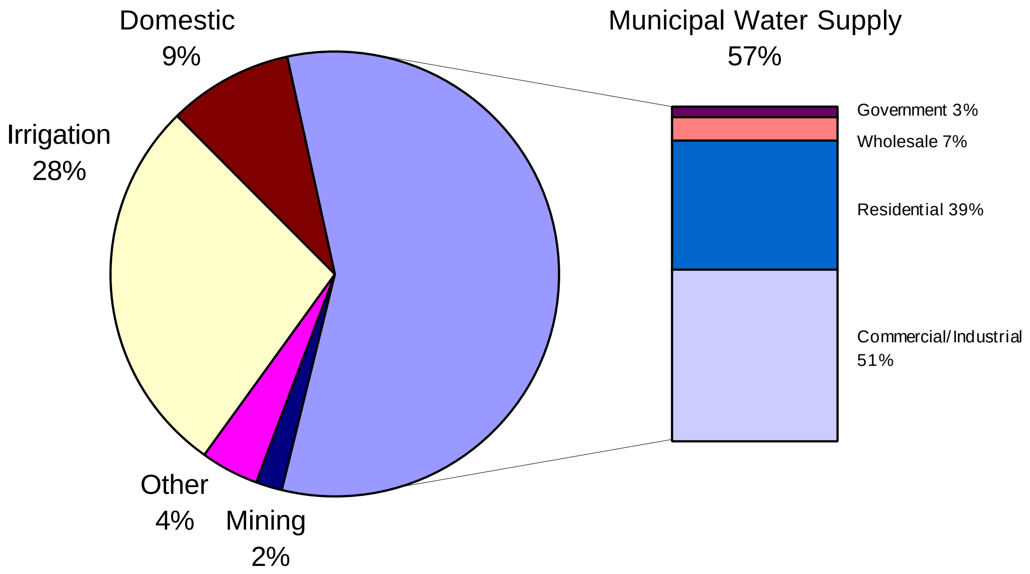


Figure HYDRO-5. Annual instantaneous flows at USGS gage 12113000, Green River near Auburn, 1937 to 1994.

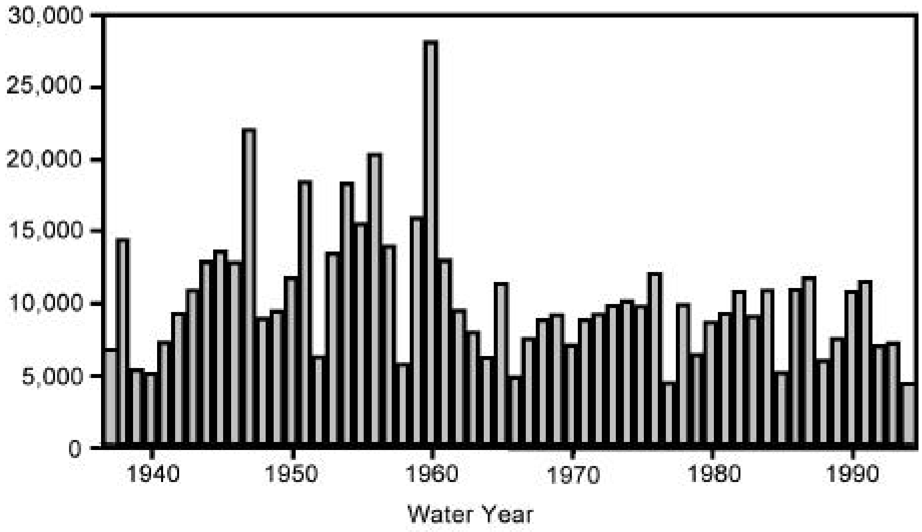


Figure HYDRO-6. Flood frequency relationships for USGS gage 12113000 Green River near Auburn, prior to and after construction of Howard Hanson Dam.

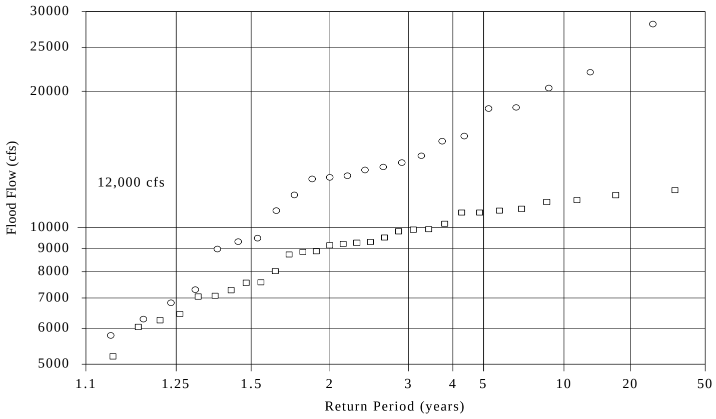


Figure 5-6a. Flood-frequency relationships for USGS Gage No. 12113000 Green River near Auburn, Washington, prior to and after construction of Howard A. Hanson Dam

Figure HYDRO-7. Daily flow duration curves, USGS gage 12113000 Green River near Auburn, prior to and after construction of Howard Hanson Dam.

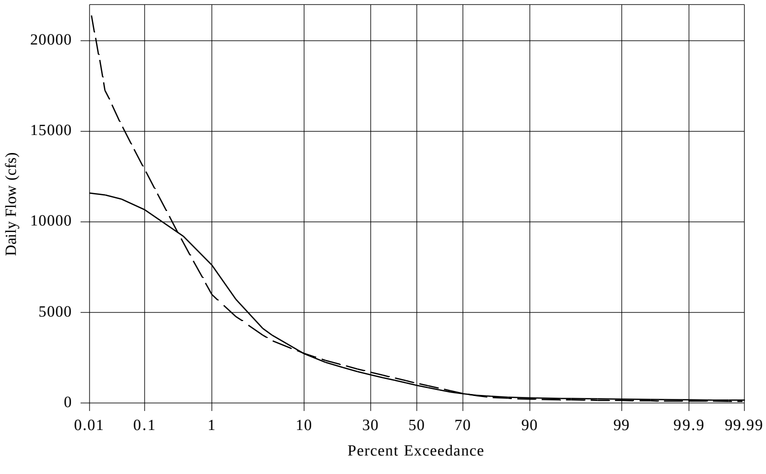


Figure 5-6b. Daily flow duration curves, USGS Gage 12113000, Green River near Auburn, Washington, prior to and after construction of Howard A. Hanson Dam.

Figure Hydro-8. Example of springtime flow reductions resulting from refill of the Howard Hanson Dam conservation pool in 1994.

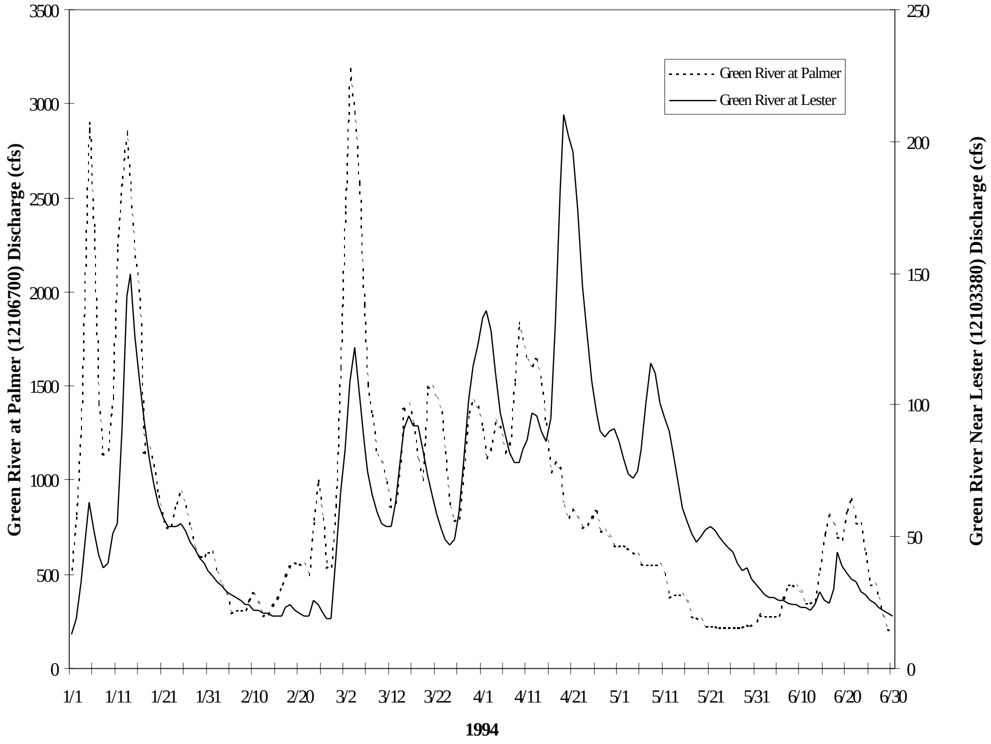


Figure Hydro-9. Average 7-day low flows in the Green River near Auburn (USGS gage 12113000) before and after construction of Howard Hanson Dam.

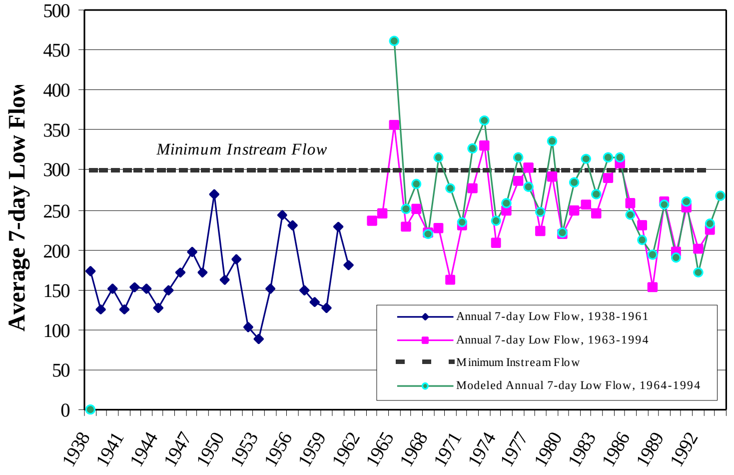
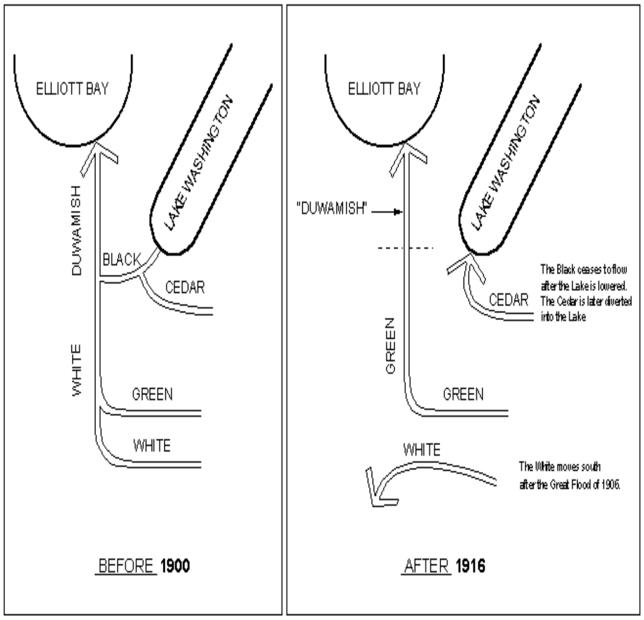


Figure Hydro-10. Configuration of the Duwamish drainage prior to 1900 and after 1916 (Source: Dunne and Dietrich 1978).



The Black ceases to flow after the Lake is lowered. The Cedar is later diverted into the Lake

The White moves south after the Great Flood of 1906.

Figure Hydro-11. Average daily flows by month for Big Soos Creek (USGS gage 12112600) and Newaukum Creek (USGS gage 12108500).

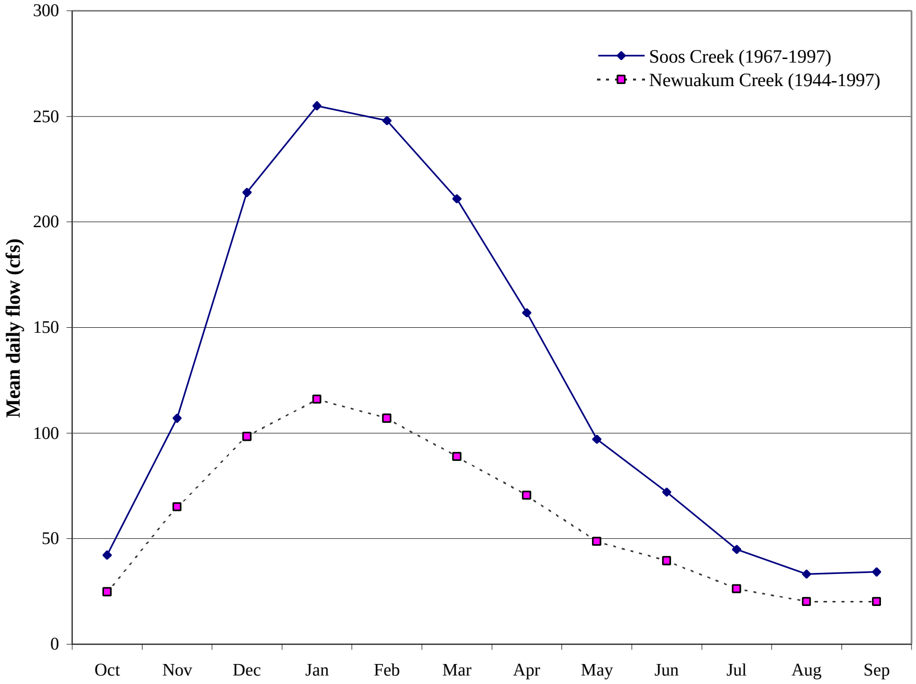


Figure HYDRO-12. Average 7 day low flows in Soos and Newaukum Creeks from 1953-1993.

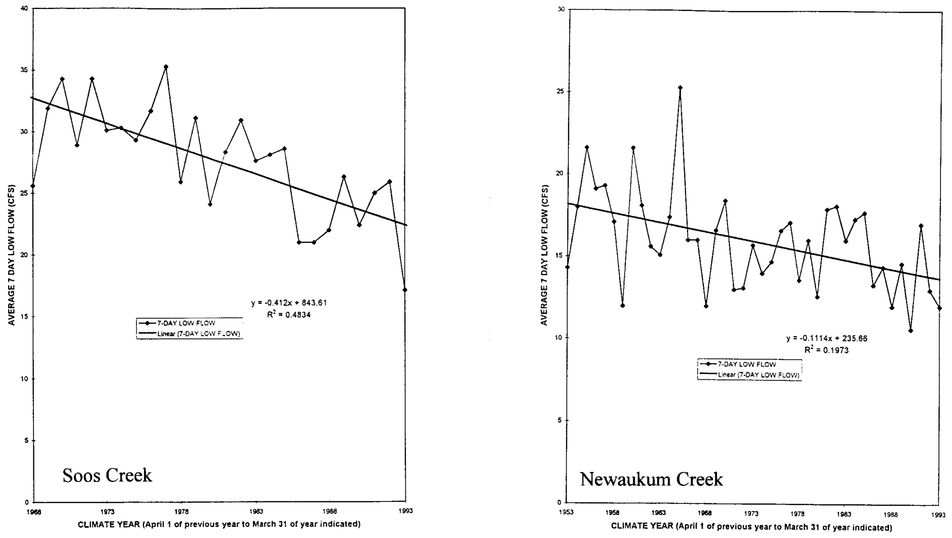


Figure HYDRO-12. Average 7-day low flows in Soos Creek (USGS gage 12112600) and Newaukum Creek (USGS gage 12108500) over the period from 1953 to 1993 (Source: Culhane et al. 1996).

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HOWARD HANSON DAM REFILL CRITERIA AND CONSIDERATIONS

Target Wild Steelhead Redd Incubation Flow: Maximum of one (1) foot stage drop from Season Spawning Flow at Auburn.

Season Spawning Flow: Average of highest ten (10) Daily Spawning Flows measured at Green River near Auburn (USGS 12-1130).

Daily Spawning Flow: Actual mean daily flow.

Steelhead Spawning Period: April 1 through June 15.

Steelhead Incubation Period: April 1 through at least July 31.

Ramp Rate Criteria: To reduce loss by stranding of salmon and steelhead fry, interim ramp rate criteria for flows under operational control of the project (does not apply to natural freshets) are as follows:

- February 16 to May 31* (salmon fry)
    - Daylight rates (1 hour before sunrise to 1 hour after sunset): No ramping.
    - Night rates (1 hour after sunset to 1 hour before sunrise): 2 inches per hour.
- June 1* to October 31 (steelhead fry)
    - Daylight rates: 1 inch per hour.
    - Night rates: 1 inch per hour.
- November 1 to February 15
    - Daylight rates: 2 inches per hour.
    - Night rates: 2 inches per hour.

* Date of shift from spring to summer criteria may require adjustment based on actual timing of steelhead fry emergence.