IMPACTS OF FLOW REGULATION ON BLACK COTTONWOOD (*Populus trichocarpa*) ALONG THE SKAGIT RIVER, WASHINGTON

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ABSTRACT

The potential impacts of regulated flows on floodplain vegetation were examined through the comparative study of free-flowing and regulated reaches within the Skagit River Basin. Floodplain forest structure and seedling recruitment were analyzed for the primary colonizing tree species. Additionally, a detailed analysis of annual hydrographs was performed using the Recruitment Box Model to determine elements of the regulated flow regime that may influence black cottonwood recruitment. Observed impacts of flow regulation included: 1) altered timing and magnitude of the snowmelt peak, 2) reduced variation in seasonal flow patterns, and 3) reduced amounts of fine sediments in the reach just below the dams. This resulted in low seedling recruitment by cottonwoods and a dominance of older age classes and later seral species below the dams. As distance below the dams increased, these impacts diminished. Suggested mitigation actions include a periodic increase in seasonal discharge between May 1 and June 30.

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INTRODUCTION

History of the Skagit

The Skagit River Watershed (Figure 1) encompasses over 8,000 square kilometers beginning in British Columbia and running south into the US through northwestern Washington State into Puget Sound. Seattle City Light owns and operates three hydro-electric dams on the River. The upper most and largest dam is Ross Dam, completed in 1949. This dam is 540 feet tall creating Ross Lake Reservoir that extends across the border into British Columbia. Downstream of Ross Dam is the 389-foot Diablo Dam completed in 1930 and Gorge Dam completed in 1924 (Seattle City Light, 2006a). The Skagit River basin is characterized by a mild wet maritime climate, receiving over 2m of precipitation annually with average annual temperatures ranging from 5-16ºC (NOAA, 2006).

Over the past 20 years, Seattle City Light (SCL) has sought to mitigate impacts from these dams through salmonid recovery programs and the purchase of over 8,000 acres of adjoining floodplains for habitat preservation. The Skagit River has stable runs of steelhead, pink, chum and chinook salmon which serve as a critical food source for the largest over-wintering population of bald eagles in the contiguous U.S. (SCL, 2006b). Additional mitigation efforts by SCL include founding of the Skagit Environmental Endowment Commission, which provides funding for projects related to environmental research, recreation and education in the upper Skagit Basin (above Ross Dam). This study is an extension of SCL's ongoing mitigation efforts in the Skagit Basin. The purpose of this study was to examine the effects of these three dams on the Skagit River floodplain forest, in particular to assess the status of black cottonwood (*Populus trichocarpa),* which can be considered a keystone species within the Skagit River floodplain ecosystem.

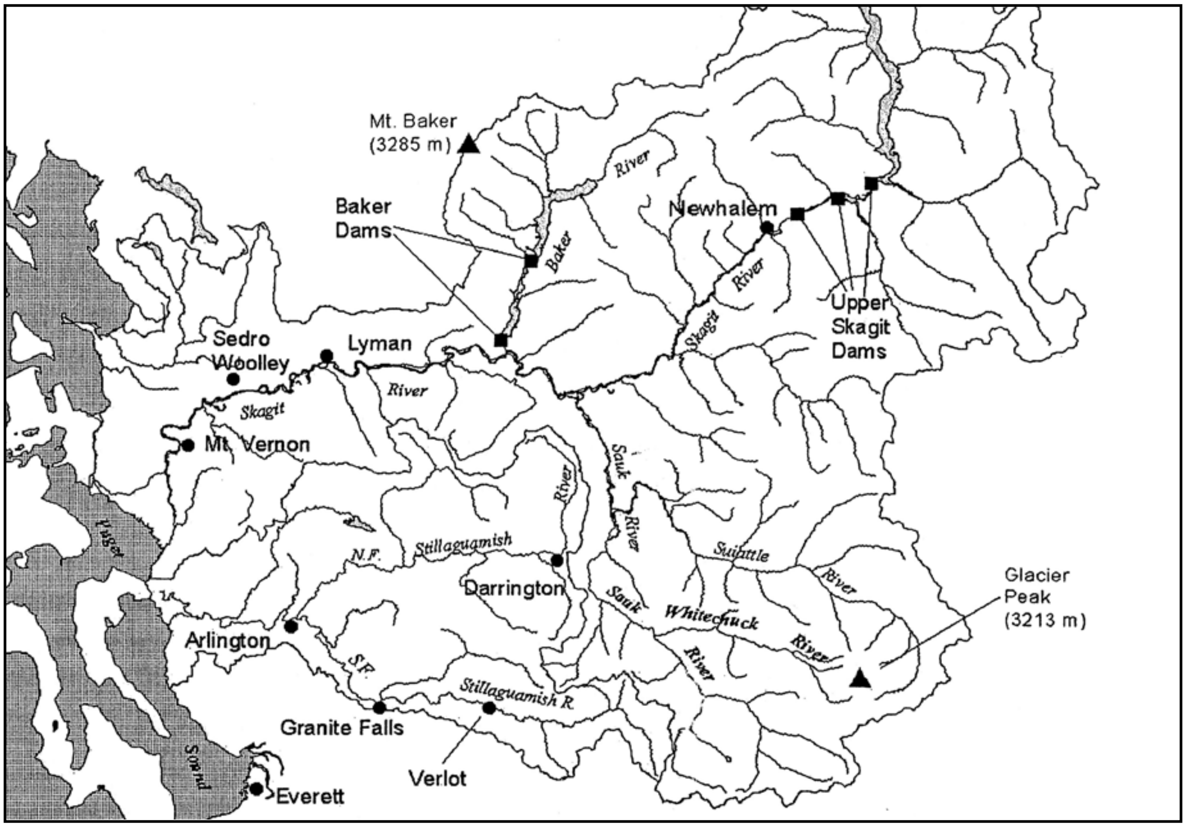


Figure 1. The Skagit River Basin within the U.S.

The Role of Cottonwoods in a Floodplain Ecosystem

Cottonwoods and willows are primary successional species along floodplain corridors throughout the western United States (Rood and Mahoney 1995, Scott et al. 1997). In semi-arid environments, the floodplain forest may be composed solely of cotton-woods (Rood and Mahoney, 1990, Stromberg 2001), while in the more mesic Pacific Northwest black cottonwoods share the riparian zone with many other species including red alder (*Alnus rubra*), western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*). Although these other species are important, cottonwood and willow are the primary colonizers of barren floodplain soils (Braatne et al. 1996, Karrenberg et al. 2002). Cottonwoods are also the largest trees, providing critical structure and diversity to flood-plain forests. Due to their role as the dominant primary successional species, cottonwoods are an excellent indicator species for assessing floodplain ecosystem integrity (Dykaar and Wigington 2000, Rood et al. 2005).

Within the floodplain environment, cottonwoods play several vital roles. They provide perching and nesting habitat for birds of prey, including bald eagles and osprey, in addition to nesting and feeding habitat for owls, woodpeckers, blue herons, bats, and numerous neo-tropical migrants (Saab 1999, Scott et al. 2003). Mule deer and elk use cottonwoods for cover and browse in summer and winter months. Beaver also use young cottonwood poles for forage and dam construction. Fish are also dependent on a healthy riparian cottonwood community for inputs of large woody debris (LWD) for habitat development and the reduction of sediment in the stream channel (Fetherston et al. 1995).

Cottonwoods stabilize geomorphic surfaces, such as banks, bars and islands, and promote sediment deposition on floodplain surfaces. During high flow events their stems and roots dissipate stream energy and act to filter sediment, capture bedload, and promote floodplain development (Fetherston et al. 1995). Cottonwoods increase floodwater retention and ground water recharge by slowing floodwaters as they move across the floodplain (Dykaar and Wigington 2000). Within the river and on the floodplain, cotton-woods are a major feature of the diverse mosaic of riverine habitats, backwater channels and ponds that support fish production, waterfowl breeding, and other wildlife (Naiman and Decamps 1997).

Throughout the western U.S. and Canada, floodplain forests dominated by cottonwoods are declining (Rood and Mahoney 1990, Dykaar and Wigington 2000). Several factors have led to this decline (Table 1). Agricultural and domestic development in flood-plain areas has dramatically reduced the extent of cottonwood forests. Livestock grazing in riparian zones has many negative effects including reduced survival of seedlings and juvenile trees from grazing and trampling (Auble and Scott 1998, Samuelson and Rood 2004). The invasion of exotic species which compete for barren soils with cottonwood seedlings has also contributed to their decline (Polzin and Rood 2000, 2005). However, the most far-reaching cause for the decline in floodplain cottonwood populations is alterations to the natural flow regime by dams and reservoirs.

Table 1. Factors contributing to the decline in riparian cottonwood forests in the western United States (modified from Braatne et al. 1996 and Rood and Mahoney 1990).

Factors Effecting Riparian Cottonwood Forests:	**Effects:**
Dams and reservoirs	Dams trap sediments and reduce peak flow events that are vital for seedling recruitment. Reservoirs inundate historic floodplain forest areas.
Water diversions	Diversions of flow for agriculture or municipal water uses reduce summer base flows causing drought stress and death in young trees.
Channelization and bank hardening	Limits the natural movements of the river channel, limiting new recruitment sites.
Agricultural development of the floodplain	Riparian forests cleared for agricultural use, due to ease of irrigation and high soil fertility.
Domestic Settlement of the floodplain	Riparian areas were some of the earliest areas to be cleared for domestic settlement in the west due to their accessibility to water, fertile soils, and relatively flat topography.
Invasion of exotic plant species	Due to the natural disturbance, exotic species invade recruitment sites and compete with cottonwood seedlings.
Livestock grazing	Livestock impact recruitment by eating and trampling young seedlings.

The Effects of Flow Regulation

Wide-ranging alterations are made to flow regimes on rivers throughout the western U.S., including altered peak and base flow discharge rates, altered timing of peak flows, and dampening of intra-annual flow variation. Differences between regulated flow regimes stem from the desired human benefits of flow regulation (Table 2); thus, the effects of these alterations on floodplain forests vary accordingly (Rood and Mahoney 1990, 1995, Rood et al. 1999, Johnson 2000, Karrenberg et al. 2002, Rood et al 2000).

Flow regulation for flood control and water storage purposes often results in reduced peak flow discharge. Lower peak discharge reduces channel migration, lessens sediment transport and deposition, lowers the amount of water inundating the floodplain, and can lessen the scouring of riverbank vegetation. These factors lead to a static channel geomorphology, diminished island and bar formation, lowered biodiversity, reduced barren floodplain area, and encroachment of upland and exotic vegetation species (Scott et al. 1996, Rood et al. 1999, Polzin and Rood 2000, Dykaar and Wigington 2000, Johnson 2002). Potential recruitment sites for primary successional species, such as cottonwoods and willows, are therefore limited.

Alterations of flow regimes for irrigation commonly lead to changes in base flow. Water stored in reservoirs and released throughout the summer can increase base flow and reduce drought mortality in floodplain vegetation; conversely diversion off stream for irrigation can lower base flows and increase drought mortality (Rood and Mahoney 1995).

Hydroelectric facilities often demand relatively constant discharge for power production and, therefore, reduce seasonal variability in flows. These facilities may also delay the timing of natural peak flows. Changes in timing and seasonal variation result in reduced reproductive success in riparian flora and fauna which have evolved a life history closely linked to natural flow patterns.

The Skagit River dams are multi-use facilities providing hydroelectric power, flood control, storage and recreation. Alterations to natural seasonal flow patterns on the Skagit

Table 2. Types of flow regime alterations and their varying effects on river geomorphology and floodplain vegetation.

Alterations to Natural Flow Regimes:	River/Riparian Effects:
Reduced Peak Flows *(Flood control and storage)*	Large flow events are vital to channel forming processes, such as sediment transport and deposition, bar formation and moving, or introducing LWD.
Reduced Base flows *(Diversion for irrigation)*	Reducing the base flows in late summer causes drought stress and mortality of vulnerable trees.
Altered Timing of Peak Flows *(Flood control, hydroelectric and irrigation)*	Cottonwoods are phonologically adapted to release seeds during the 2-3 weeks of normal peak flows during late May and early June. Early or late peak flows limit successful recruitment.
Daily Pulsed Flows *(Coincides with peak demand from hydroelectric facilities)*	Constantly changing water levels can decrease bank stability and cause excessive erosion and seedling mortality.
Reduced Intra-Annual Flow Variation *(Constant flow for hydroelectric, irrigation, etc.)*	Natural variation in flow promotes adaptability and drought tolerance in riparian trees; without this variation genetic diversity declines.
Elevated Base Flows *(Increased summer demand downstream for irrigation and municipal water)*	Elevated base flows can improve the health of riparian trees by reducing drought stress, but reduces survival of seedlings.

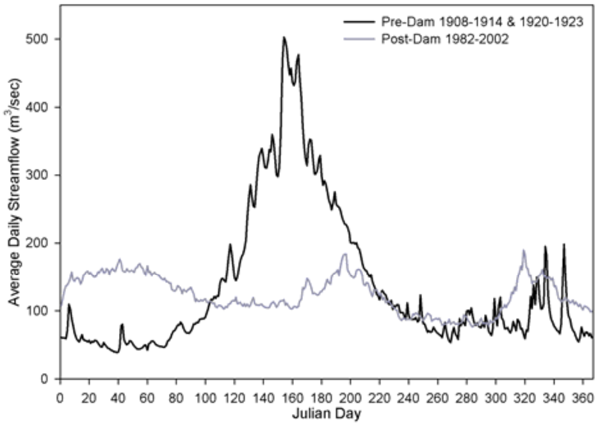


Figure 2. A comparison of the historic (1908-1914, 1920-1923, prior to dam construction) and the current (1982-2002) seasonal flow patterns for the Skagit River at Newhalem.

River by these facilities (Figure 2) include, reduced peak flows, elevated base flows, altered timing of peak flows, and reduced variation in seasonal flows. These alterations lead to changes in the stream and on the floodplain that affect cottonwood recruitment and survival.

Instream Flow Requirements of Cottonwoods - The Recruitment Box Model

Although cottonwoods are phreatophytes, drawing water directly from groundwater sources, their populations are maintained by distinct flow requirements (Dykaar and Wigington 2000, Rood and Mahoney 2000). In particular, the reproductive phenology of cottonwood is closely associated with natural flow regimes (Braatne et al. 1996, Rood and Mahoney 1998). Many riparian cottonwood forests have declined in response to altered river flows to better suit human needs (Rood et al 1999, Williams and Cooper 2005, Fierke and Kauffman 2005).

There has been extensive research on cottonwoods within the *Aigeiros* section of *Populus* which is native to semi-arid regions of the western US and Canada (e.g. *P. deltoides*) (Rood and Mahoney 1990, Cordes et al. 1997, Johnson 2000, Rood et al. 2003, 2005). These studies have documented a distinct set of flow requirements necessary for successful reproduction. Research involving black cottonwood is less common; however, a few studies have shown their flow requirements to be similar to *Aigeros* taxa (Mahoney and Rood 1998, Polzin and Rood 2005). In the Pacific Northwest, summer precipitation also reduces the risk of drought induced mortality. Winter storm events appear to provide the dominant disturbance needed to provide barren floodplain surfaces for seedling colonization.

Table 3. Important instream flow requirements to sustain riparian cottonwood populations.

Flow Requirements:	**Importance to Cottonwood Sustainability:**
Large peak flows in late May and early June	Inundation of the floodplain to recharge ground water aquifers and create nursery sites for seed germination
Peak flow reduced at a rate of ~2.5 cm/day throughout June and July	Root systems of newly germinated seedlings must stay in contact with the capillary fringe as the water levels recede
Maintenance of historic low flow levels	Cottonwoods are adapted to natural flows but will suffer drought stress if summer base flows are depressed
Seasonal variation in flows	Promotes drought tolerance by supporting deep root growth and allows recruitment at different floodplain elevations each year – promotes genetic diversity within and between populations

A distinct series of events lead to successful seedling recruitment for all cottonwood species (Table 3). The process of establishment is initiated when a large peak flow scours out existing vegetation and deposits sediment to form barren nursery sites (Rood and Mahoney 1995, Scott et al. 1996, 1997, Mahoney and Rood 1998, Shaffroth et al. 2002). In semi-arid environments, these scour flows are associated with the seasonal snowmelt peak; however, in the Pacific Northwest these scour flows generally occur as late fall or winter storm peaks. Following the creation of nursery sites, seeds must be dispersed and seedlings established at elevations that are safe from desiccation, scour and sediment deposition (Johnson 2000, Polzin and Rood 2005). Dispersal is optimal when the seasonal snowmelt peak occurs prior to or during the period of seed release (Scott et al. 1996, Mahoney and Rood 1998). As the river stage declines, seeds carried both by the wind and the water are deposited at various elevations on the floodplain (Braatne et al. 1996, Mahoney and Rood 1998, Polzin and Rood 2000). Once seeds are deposited onto barren moist soils, they typically germinate within 24 hours (Braatne et al. 1996). After germination, seedling roots strive to maintain contact with the declining soil moisture as river water levels recede. Research has shown that stage decline rates of 1-2.5cm/day in coarse sediments and up to 5.0cm/day in fine sediments are optimal for root growth and survival of seedlings (Mahoney and Rood 1991, 1992, Amlin and Rood 2002). Following seedling establishment, summer base flows must remain high enough to prevent drought mortality. Large flood events within the first two years of establishment may reduce recruitment as young seedlings are highly susceptible to scour and burial by deposition (Johnson 2000, Polzin and Rood 2005). As a result of natural variation in the annual flow patterns, favorable conditions do not occur every year. Typically, in non-regulated systems, high levels of cottonwood recruitment occur once every 5-10 years (Bradley and Smith 1986, Scott et al. 1997, Mahoney and Rood 1998).

The Recruitment Box Model (RBM) developed by Mahoney and Rood (1998) has been used to assess the relationship between seasonal flow patterns and cottonwood seedling establishment and survival. The model seeks to align cottonwood reproductive phenology and stream flow during a window of opportunity i.e. the “recruitment box.” The degree of the alignment between these factors provides an estimate for the likelihood of successful recruitment. The relationship between flow and seedling establishment is evaluated in terms of seasonal changes in river stage. River stage is the elevation or height of water in the channel, which is a function of discharge and channel shape. A stage hydrograph quantifies the change in water levels through time. The conceptual basis of the RBM is illustrated in Figure 3 using a stage hydrograph during the months vital to

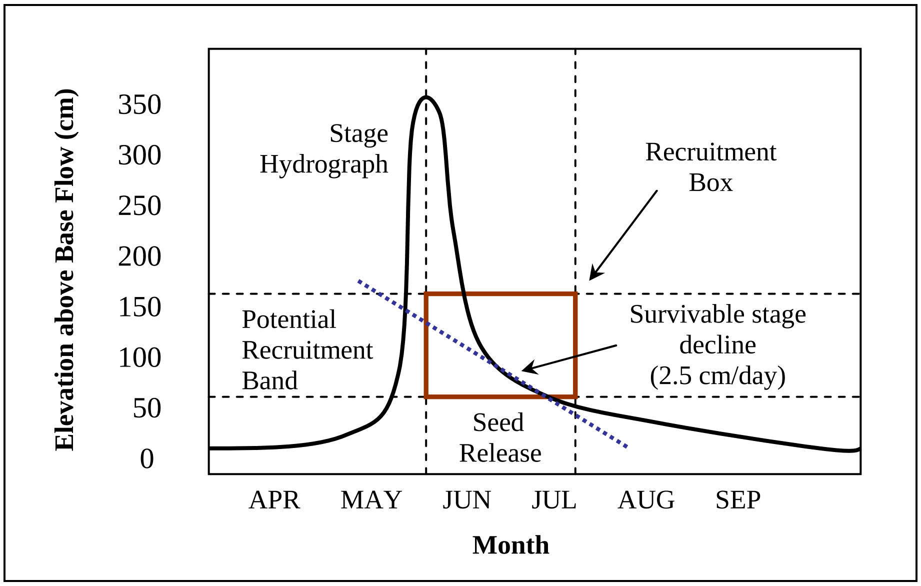


Figure 3. The conceptual basis of the Recruitment Box Model showing optimal flow conditions for cotton-wood seedling establish-ment (modified from Mahoney and Rood, 1998).

cottonwood recruitment. River stage, rather than discharge, is used to estimate the range of floodplain elevations suitable for seedling recruitment sites.

In the model, river stage above base flow is plotted against time and the "recruitment box" is aligned with the seasonal hydrograph (Figure 3). The vertical dimension of the recruitment box represents the potential elevation zone suitable for seedling recruitment (60 to 150cm above base flow) and the horizontal dimension represents the period of seed release (May - June). The final component of the model is the survivable rate of stage recession, which typically ranges from 1-2.5 cm/day. Together these elements provide an estimate for successful cottonwood recruitment. If river stage is declining through the box, cottonwood seeds have the opportunity to establish at suitable elevations on newly exposed sediments. If the rate of water level decline follows the line of survivable stage recession, the threat of seedling desiccation is diminished. If both conditions are met, seedling establishment is promoted. Practical application of the RBM is achieved by analyzing quantitative flow criteria (i.e. daily stage and discharge data) to estimate the likelihood of successful recruitment in a given year (Braatne et al. 2006).

OBJECTIVES

This study was designed to assess the effects of the upper Skagit River dams on floodplain vegetation, and more specifically on the black cottonwood, along the Skagit River below Newhalem. A three way comparison was made between a regulated river segment (Skagit River – Newhalem to the confluence with the Sauk), an unregulated river segment (Sauk River – above the Whitechuck River to the confluence with the Skagit River), and a partially-regulated river segment (Skagit River below the confluence with the Sauk River). The Sauk River is the Skagit's largest non-regulated tributary, flowing into the river approximately 30 river miles below Diablo Dam. By comparing the species composition, age class, and seedling recruitment of colonizing woody plants between these three areas, we could assess the relative influence of regulated flows on floodplain vegetation. In addition to vegetation analysis, the RBM was used to highlight elements of the Skagit River flow regime that may effect recruitment by cottonwoods and, therefore, reduce the overall integrity of floodplain forests. The main objectives were:

1) Document the changes between historic and current flow regimes on the Skagit and Sauk Rivers, comparing differences in flow between regulated, unregulated, and partially regulated reaches.
2) Compare species distribution, composition, age classes, and growth rates of the dominant woody colonizing species in unconstrained reaches of the Skagit and Sauk Rivers.
3) Document the age structure of black cottonwood along the Skagit and Sauk Rivers compare with historic flow regimes.
4) Analyze flow regimes using the Recruitment Box Model (RBM) to determine how the Skagit River flow regime may be effecting cottonwood recruitment.

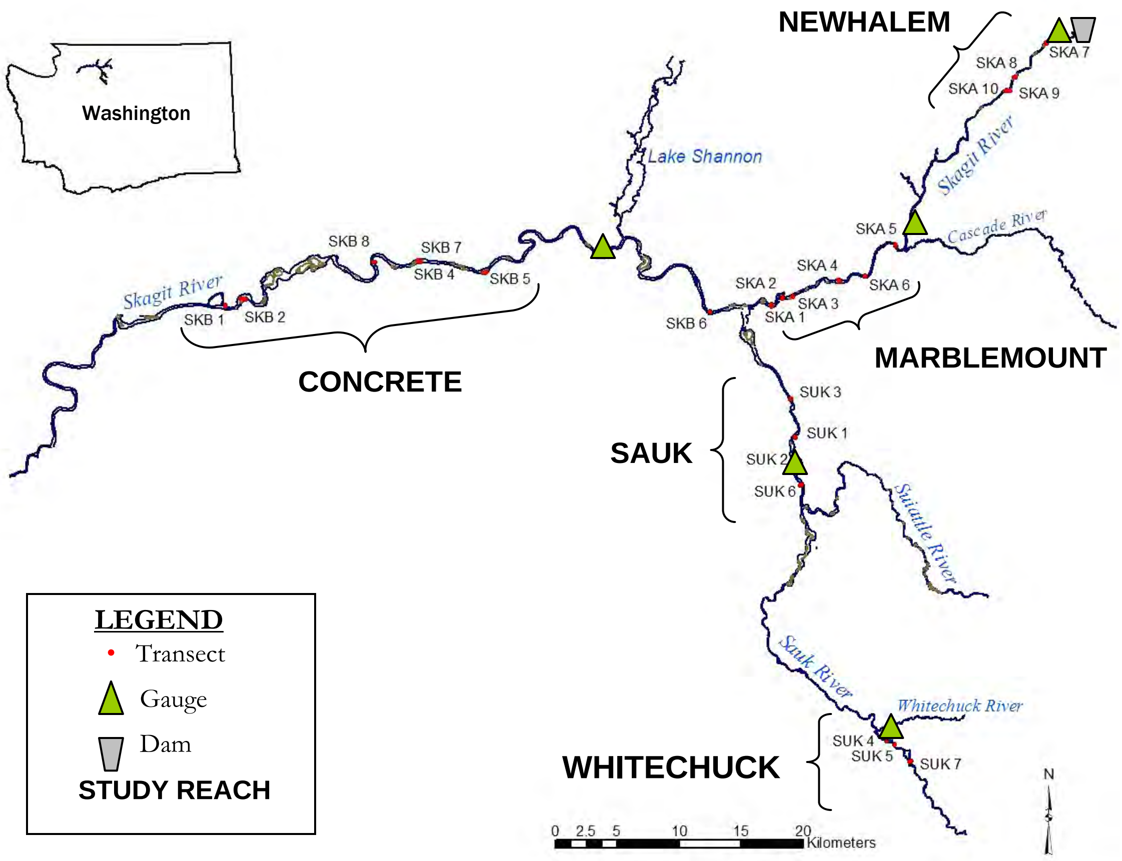


Figure 4. Study reach and transect site locations with associated USGS gauging stations.

METHODS

Site Selection

Study sites were selected in three major reaches for comparison of flow regulated, unregulated, and partially-regulated river reaches (Figure 4). The Skagit River from Newhalem to the confluence with the Sauk River (~27 river miles) is a flow regulated reach. The Sauk River (river miles 0-40) is a free flowing river with minimal land-use alterations. The Skagit River below the Sauk River confluence to the downstream end of the Ross Island region (~40 river miles) is a partially-regulated reach due to sediment and flow inputs from the Sauk River. The Sauk River and the Skagit from Newhalem to its confluence with the Sauk share similar discharge rates and geomorphic features. These similarities allow the assessment of floodplain vegetation characteristics in relation to flow regime with minimal confounding factors. The

Skagit River below the Sauk River confluence provides insight on the influence of a large (~50% of the total discharge) unregulated tributary upon a flow-regulated system.

In order to reduce confounding factors associated with tributary inputs, discharge and elevation, the upper segments of both rivers were separated into upper and lower reaches (Table 4). The resulting five study reaches are referred to by the names associated with their respective USGS gauges. These study areas are: 1) Newhalem – the uppermost reach of the Skagit River, from Diablo Dam to the confluence with the Cascade River, 2) Marblemount – the Skagit River from the mouth of the Cascade River to the Sauk River confluence, 3) Whitechuck – the uppermost reach of the Sauk River to the confluence with the Whitechuck River, 4) Sauk – the reach of the Sauk River from the mouth of the Suiattle River to the Skagit River confluence, and 5) Concrete – the Skagit River below the Sauk River confluence to the bottom of Ross Island (Figure 4).

Within each study area, transects were located in unconstrained reaches with the highest probability of cottonwood recruitment, including islands, point bars, and sidebars (Braatne et. al 1996, Dykaar and Wigington 2000). Since river access was limited, there was an uneven number of transects between study reaches. Data was thus pooled by study reach. Four transects in the Newhalem reach, had an overall length of 314m. The Whitechuck reach had three transects with a total length of 334m. The Marblemount reach had six transects totaling 964m and the Sauk reach had four transects covering 658m. The Concrete reach had seven transects with a total length of 1446m. The axis of each transect was marked with 2-4 permanent rebar posts 1 meter in length and GPS locations recorded with sub-meter accuracy using a Trimble GPS Pathfinder ProXRS (Trimble Navigation Inc., USA).

Table 4. Average geomorphic characteristics of study reaches.

Stream Reach	Channel Gradient	Sinuosity	Channel Width (m)	Floodplain Width (m)	Valley Width (m)
Newhalem	0.00286	1.13	71	490	873
Marblemount	0.00177	1.10	152	1360	2508
Whitechuck	0.00697	1.17	46	471	510
Sauk	0.00271	1.12	169	578	1003
Concrete	0.00082	1.22	224	1328	2381

Flow Regime Analysis

Data from USGS gauges located within each reach (Figure 4) were used to compare flow regimes between reaches. The gauges used were: Newhalem - USGS gauge 12178000 (Skagit River at Newhalem), Marblemount – USGS gauge 12181000 (Skagit River at Marblemount), Whitechuck – USGS gauge 12186000 (Sauk River above the Whitechuck River), Sauk – USGS gauge 12189500 (Sauk River at Sauk), and Concrete – USGS gauge 12194000 (Skagit River at Concrete). Average daily streamflow data and drainage area were obtained via the USGS website (http://wa.water.usgs.gov/data/realtime/htmls/ skagit.html) for each gauge for 1982-2002. Average daily discharge was converted to m^3/sec and divided by drainage area to produce average annual hydrographs normalized by watershed area for each gauge. All graphing was performed with Sigma Plot 9.0 (Systat Software, Inc., 2004). Twenty years of contiguous data was not available for Newhalem prior to dam construction; therefore, all available data (1908-14, 1920-23) were used to construct the historic discharge hydrograph. Historic peak flows were constructed using peak flow data (1929-2004), converted to m^3/sec then plotted. Continuous data were not available for the Skagit River at Marblemount; therefore, all available data (1944, 1947-1957, 1976-2004) were tabulated.

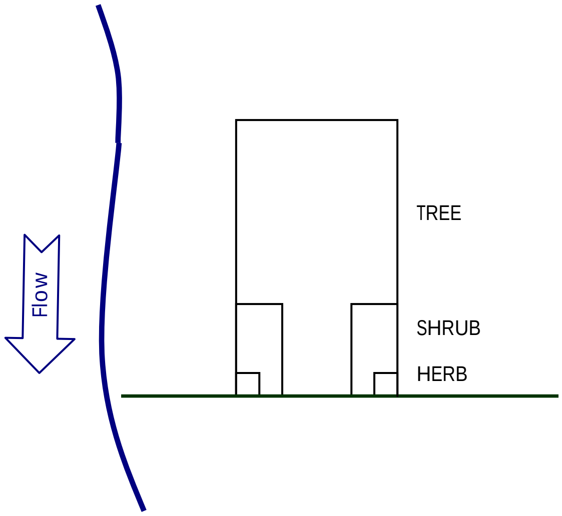
Vegetation Sampling

Field data on vegetation were collected between July 1 - August 30, 2004 and 2005. Belt-transect sampling techniques were used to analyze floodplain vegetation structure. Transects were established perpendicular to the channel running from the water's edge into mature riparian forest and ranged from 80-490m in length depending on floodplain features. Transects were surveyed to determine the elevation of vegetation plots relative to mean base flow water surface levels. A professional crew from Larry Steele & Associates, Bellingham, WA conducted these topographic surveys using a Leica total station (±1-2cm accuracy).

Transects were divided into distinct geomorphic and vegetative patches, including gravel and sand bars, low, mid and high floodplains, slopes to terraces, back-channels, and terraces. Within each patch, the dominant vegetative cover type was recorded (i.e. alder pole stand, willows or mature cottonwoods) and nested herb, shrub and tree plots were randomly located perpendicular the transect line. Herb plots were 1x1m, shrub plots 2x4m, and tree plots 5x10m, 5x20m or 10x25m depending upon the size class of the trees. Shrub and herb plots were nested within tree plots in order to maintain equal elevation relative to base flow water level (Figure 5).

Within each tree plot, percent cover, stem counts, and diameter at breast (1.3 m) height (DBH) of all trees were recorded. Within shrub

Figure 5. Nested arrangement of tree, shrub, and herb plots.



and herb plots, percent cover by species was also recorded. For analysis, field estimates of percent cover were converted to an octave scale and the midpoints of each octave class used to minimize sampling errors while still preserving fine-scale differences. The octave classes used were: 0 (0% cover), 1 (1%), 2 (2-4%), 3 (5-9%), 4 (10-18%), 5 (19-35%), 6 (36-72%) and 7 (73-100%).

In addition to the plot data, point and line-intercept data were collected along the entire length of the transect. Canopy cover of woody species intersecting the plane of the transect were recorded along the length of each transect. Substrate type and herbaceous species present were recorded every meter. Substrate was classified into seven categories using the Wentworth scale: 1) Bedrock, 2) Large Boulders, (>256mm), 3) Cobble (64-256mm), 4) Gravel (2-64mm), 5) Sand (0.06-2mm), 6) Fines (<0.06mm), and 7) Duff (organic material) (Gordon et al. 1992). Seedling counts of tree species were also collected in 0.1m^2 quadrats at 1-meter intervals along length of the transect.

A complete species list was compiled (see Appendix A) with common species tabulated by study reach (Table 5). Common species were those that occurred in one half or more transects within a study reach. Willow species were not classified below genus due the high level of hybridization among species in this area and the associated difficulties in accurate identification. All plant identifications were made with reference to Hitchcock and Cronquist (1973).

Table 5. Common herbaceous and woody vegetation species that occurred in each study reach.

Forbs:	**Newhalem**	**Marblemount**	**Whitechuck**	**Sauk**	**Concrete**
Adenocaulon bicolor			X		
Anaphalis margaritaceae	X	X	X		
Circaea alpina	X	X	X	X	
_Cirsium arvense_*					X
_Cirsium vulgare_*		X			
Claytonia perfoliata	X	X			
Dicentra formosa				X	
_Digitalis purpurea_*		X			
Equisetum arvense		X	X	X	X
Equisetum hyemale				X	X
Fragaria vesca	X	X	X		
Galium triflorum			X		
Geum macrophyllum			X		
_Geranium robertianum_*		X			
_Hypericium perforatum_*	X	X	X		
_Lactuca muralis_*		X			
Petasites palmatus		X			
Polystichum munitum	X			X	
_Ranunculus repens_*			X		X
_Rumex acetosella_*		X	X		X
_Silene dichotoma_*		X			
Stachys cooleyae		X			X
Tanacetum bipinnatum ssp. _huronense_*	X	X			X
Tolmiea menziesii	X	X	X	X	
Trientalis europaea var._arctica_	X				
Woody Species:					
Abies grandis			X		
Acer macrophyllum	X	X		X	
Alnus rubra	X	X	X	X	X
Cornus stolonifera	X	X			X
Popl;us trichocarpa	X	X	X	X	X
Pseudotsuga menziesii	X				
Salix sp.	X	X	X	X	X
Thuja plicata	X				
Tsuga heterophylla	X			X	
Acer circinatum	X		X	X	
Corylus cornuta		X			X
_Cystisus scoparius_*		X		X	
Lonicera involucrata	X	X	X	X	
Oemleria cerasiformis	X	X	X	X	X
Rhamnus purshiana	X			X	
Ribes sanguineum	X				
Rosa gymnocarpa	X				
Rosa nutkana				X	
_Rubus discolor_*		X			X
Rubus parviflorus	X		X	X	X
Rubus spectabilis	X	X	X	X	X
Rubus ursinus	X	X	X	X	X
Sambucus racemosa				X	
Symphoricarpos albus	X	X	X	X	X
***Non-native Species**					

Within each distinct geomorphic and vegetative patch, 2-4 representative trees were cored with an increment corer to determine age. Patches containing saplings were sampled by obtaining trunk cross-sections. For each tree/sapling sampled, diameter at breast height (1.3m), diameter at core height and species were recorded. Cores were affixed to a wood backing and both cores and cross-sections were sanded with 220 grit sandpaper. Rings were counted, adding two years to account for core height, under magnification by three independent observers with average age (±1-2 years) determined for each core or cross-section.

Data Analysis

Channel gradient, sinuosity, valley, and floodplain width were calculated by the Skagit River Coop on floodplain polygons and presented in an ARC-VIEW shapefile entitled Skagit System Floodplain Reaches (last revised in 2001). Channel width measurements were made from USGS 1:10,000 topographic quad maps and represented the mean of three measurements taken of the channel in the area of each transect.

Line intercept data on canopy cover were used to assess the abundance of major riparian tree and shrub species relative to stream reach. The total transect length covered by each species was tabulated and then expressed as a percent of the total transect length in the reach. Canopy cover of tree species was also recorded for distinct age classes to determine the relative abundance of mature and juvenile trees. Point intercept data were used to determine the relative abundance of herb species and categorize substrate size classes. The occurrence of each herbaceous species and substrate class was calculated as the percent of occurrences out of the total number possible. Tree seedlings were counted on exposed substrates adjacent to the river channel, with their distribution and abundance quantified relative to mean base flow water level. Mann-Whitney Rank Sum tests and Chi-square analysis of seedling distribution data were performed with Sigma Stat 3.1 (Systat Software, Inc. 2004).

Cottonwood age and diameter data were plotted to compare growth rates between reaches. Linear and polynomial relationships between age and diameter of trees <40 years old were explored through regression using Sigma Stat 3.1. Overall differences between reaches were also assessed by performing an ANOVA on the ratio of diameter to age.

Cover and density data collected in tree shrub and herb plots will be used to explore the multivariate relationships between plant species and key environmental variables, using detrended correspondence analysis (DCA, unconstrained ordination) and canonical correspondence analysis (CCA, constrained ordination). This analysis will be performed by Dr. Braatne, so will not be discussed in this thesis.

Recruitment Box Model Analysis

The Recruitment Box Model (RBM) was applied to regulated, unregulated, and partially-regulated reaches using discharge data from the lowest gauge within each reach. Five RMB criteria (Table 6) were applied to seasonal flows from 1980 to 2001 (period of time encompassed by cottonwood age data). Each criterion focused on a key component of the flow regime and was assigned an individual score based on the influence of that component on seedling recruitment. All scores were totaled, with a possible overall score of 8. Any year with a majority of favorable conditions (i.e. a score ≥4) was considered favorable for cottonwood seedling recruitment. Since the RBM was developed on semi-arid rivers, minor modifications were made to adjust the model to the more mesic climate of western Washington. These modifications included: 1) separating the seasonal snowmelt peak from disturbance flow, 2) extending the time of influence of disturbance flows, and 3) including a lethal scour flow criteria.

Criterion 1: *Disturbance flow (Q_{max}).* A disturbance flow (Q_{max}) must occur prior to seed release to scour existing vegetation and deposit sediment to provide barren nursery sites. However, this disturbance flow need not be the seasonal snowmelt peak. In the mesic climate of western Washington, winter storm peaks have the power to reshape floodplain surfaces, whereas seasonal snowmelt peaks are more associated with floodplain inundation and seed dispersal. It was determined that the smallest flow to have significant scour power would be a 3 year flood. Additionally, larger floods would have more power to create nursery sites and thus extend their “influential time window” for recruitment in relation to their magnitude. Three, 5, 10 and 25 year return-interval flood discharge levels were determined using a log-Pearson Type III flood frequency analysis for each gauge, using all available data (Appendix B). Analyzing patterns seen in tree age data in relation to historic peak flow events, the “influential time window” associated with a flood event was determined to be between 1 and 4 years. Three, 5, 10, and 25 year return-interval flood events were assigned 1, 2, 3, and 4 year “influential time windows,” respectively. High magnitude events were given higher weighting in the overall score because their ability to create barren floodplain areas increased with flood magnitude.

Criterion 2: Timing of the Seasonal Peak (Q_{sp}). Cottonwood physiology and seed dispersal mechanisms require the seasonal peak to occur during the period of seed release. Within these river basins, the majority of cottonwood seed release occurs during May and

June, and thus the optimal period for the seasonal peak was designated as May 1 to June 30.

Criterion 3: Stage Recession Rate. Exact changes in stage associated with declining discharge can be calculated from channel cross-sections; however, this method is labor intensive and channel cross-sections were not available for the Skagit and Sauk Rivers over the last 20 years. Since the RBM gives an overall rating to the flow conditions in a given year, a more generalized stage-discharge relationship was calculated for each reach. Daily discharge and stage measurements from 1987-2005 were plotted for each gauge and a third order polynomial regression trendline fitted to the data. This relationship was then used as the general stage discharge relationship for the reach, and thus accounted for the effects of inter-annual and intra-reach variations in channel morphology. The use of a generalized rating curve in each reach only provides an approximation of changes in river stage; however this approximation was acceptable due to the coarse scale of this analysis. The overall daily stage decline for each reach

Table 6. Definition of the five quantitative flow criteria used in the application of the Recruitment Box Model to the Skagit and Sauk Rivers and the numerical scores associated with each.

Hydrograph Element	**Scoring Criteria**	**Score**
1. Magnitude of Disturbance Flow (Q_{max})	25+ yr (4 yrs influence)	1
	>10 yr (3 yrs influence)	1
	>5 yr (2 yrs influence)	0.66
	>3 yr (1 yr influence)	0.33
	<3 yr	0
2. Timing of Seasonal Peak (Q_{sp})	Q_{sp} between May 1st and June 30st	1
	Q_{sp} too early or late	0
3. Stage Recession Rate	$M \leq 20$	1
Rates: Favorable (<5cm/day), Stressful	$20 < M \leq 30$	0.5
(5-10 cm/ day), Lethal (>10cm/day)	$M > 30$	0
M = (prop. Lethal * 3 + prop. Stressful)/3	Stage of Q_{sp}< 60cm	0
4. Late Summer Flow (Q_A)	$Q_A \geq Q_{7,10}$	1
Q_A = Mean August discharge	$Q_A < Q_{7,10}$	0
$Q_{7,10}$ = 7-day, 10-year low flow		
5. Post-Recruitment Scour Flow (Q_{sc})	$Q_{sp} > Q_{sc}$ (0-2 yrs post recruitment)	4
	$Q_{sp} \approx Q_{sc}$ (0-2 yrs post recruitment)	2
	$Q_{sp} < Q_{sc}$ (1-2 yrs post recruitment)	2
	$Q_{sp} < Q_{sc}$ (0-1 yr post recruitment)	0
	Total Score	8

was calculated by applying the general stage discharge relationship to daily discharge data at each gauge. A three-day moving average was used to smooth out discharge variations between days. Once the daily stage declines were calculated, the number of favorable (<5cm/day), stressful (6-10cm/day), and lethal (>10cm/day) days were totaled for the length of the stage recession. Finally, weighted mortality coefficients (M) were calculated for each year using the proportions of lethal (L) and stressful (S) days ($M=(3L+S)/3$). Overall scores were based on these mortality coefficients. Years with $M<20$ were considered favorable and those with $M>30$ were unfavorable. An overriding factor was also added to the stage decline criterion: the seasonal peak must also rise to the 60cm above base flow stage requirement of the model. Any year in which the stage of the river did not rise to >60cm above mean base flow water level was considered unfavorable for seeding establishment regardless of the stage recession rate.

Criterion 4: Late Summer Flow (Q_A). While late summer drought is less common in western Washington than in northern arid environments, river levels must still remain high enough throughout August (the hottest and driest month on the Skagit) to ensure water availability to newly established seedlings. For our purposes a 7-day, 10-year low flow ($Q_{7,10}$) was calculated for each reach by performing a log-Pearson Type III low flow frequency analysis on 7-day average low flows for each year on record at each gauge (Appendix C). An overall score was based on the comparison of average August discharge (Q_A) to $Q_{7,10}$. Years with $Q_A \geq Q_{7,10}$ were considered favorable for seedling survival and years with $Q_A < Q_{7,10}$ unfavorable.

Criterion 5: Post-Recruitment Scour Flow (Q_{sc}). A large scouring flow (Q_{sc}) in the winter subsequent to any recruitment event may remove a majority of the newly established seedlings. The effects of Q_{sc} are reduced as young trees become more established. Because young seedlings are highly susceptible to scour and sedimentation, the overall score of the scour flow criterion was weighted equally to all four other RBM criteria. Years with $Q_{sc} > Q_{sp}$ within the first year post-recruitment were considered unfavorable for seedling survival. If $Q_{sc} \approx Q_{sp}$ or if $Q_{sc} > Q_{sp}$ 1-2 years post establishment, it was considered to have a limited effect. Only years with no scour flow greater than the seasonal peak, in the subsequent two years, were considered favorable for cottonwood recruitment.

RESULTS

Seasonal Flow Patterns

Dams along the Skagit River have significantly altered seasonal flow patterns (Figure 2). First, the magnitude of the seasonal snowmelt peak has been severely attenuated, dropping from an average peak flow of $500m^3$/sec to less than $200m^3$/sec. Second, timing and duration of snowmelt runoff has been altered. Duration of peak flow has been reduced from 140 days to 70 days and the timing of the maximum peak flow has been delayed by 40 days. Historically, seasonal runoff began in early April, peaked the first week of June (~day 155) and gradually receded into late August or early September. Currently seasonal hydrograph rise begins in mid June, reaches maximum discharge in mid July (~day 195) and then declines through late August. Base flows in spring and fall have also been elevated. Spring base flow has increased by approximately $100m^3$/sec in response to reservoir draw down to collect snowmelt runoff. Finally, the overall variation in the yearly flow has been reduced. Historically, the difference between base and peak flow discharge was ~$450m^3$/sec, whereas the current flow regime produces a change of ~$100m^3$/sec throughout the year. These findings assume temporal stationarity; that the effects of climate change are minor in comparison to those of flow regulation. It is also important to note that while this is a snowmelt-dominated system, seasonal hydrographs are also strongly affected by winter rain events.

A comparison of current (1982-2002) seasonal flow patterns, normalized by drainage area, between study reaches (USGS gauge 12178000 Skagit River at Newhalem with a drainage area of $3043km^2$, and gauge 12186000 Sauk River above the White Chuck River with a drainage area of $394km^2$) show several alterations of the flow regime in the upper reaches due to flow regulation (Figure 6A). Normalization removes the effects of differential watershed size and shows a larger magnitude of discharge relative to watershed

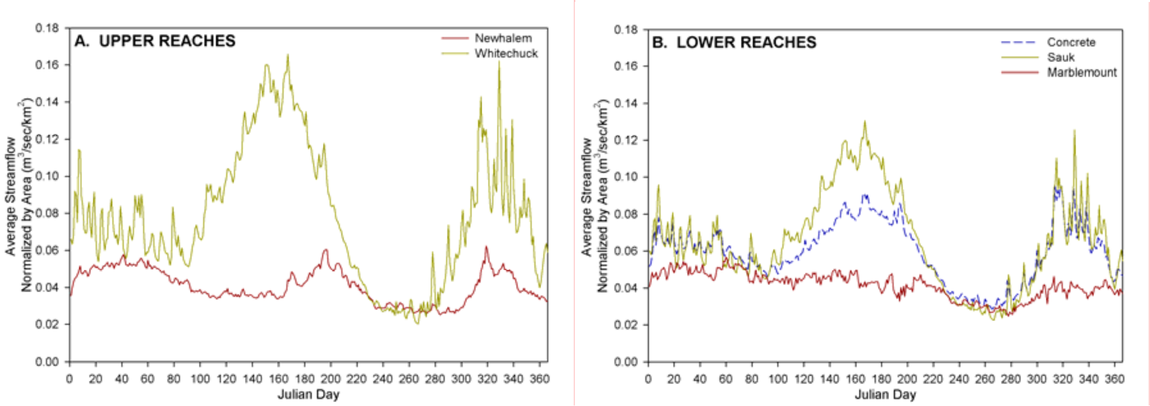
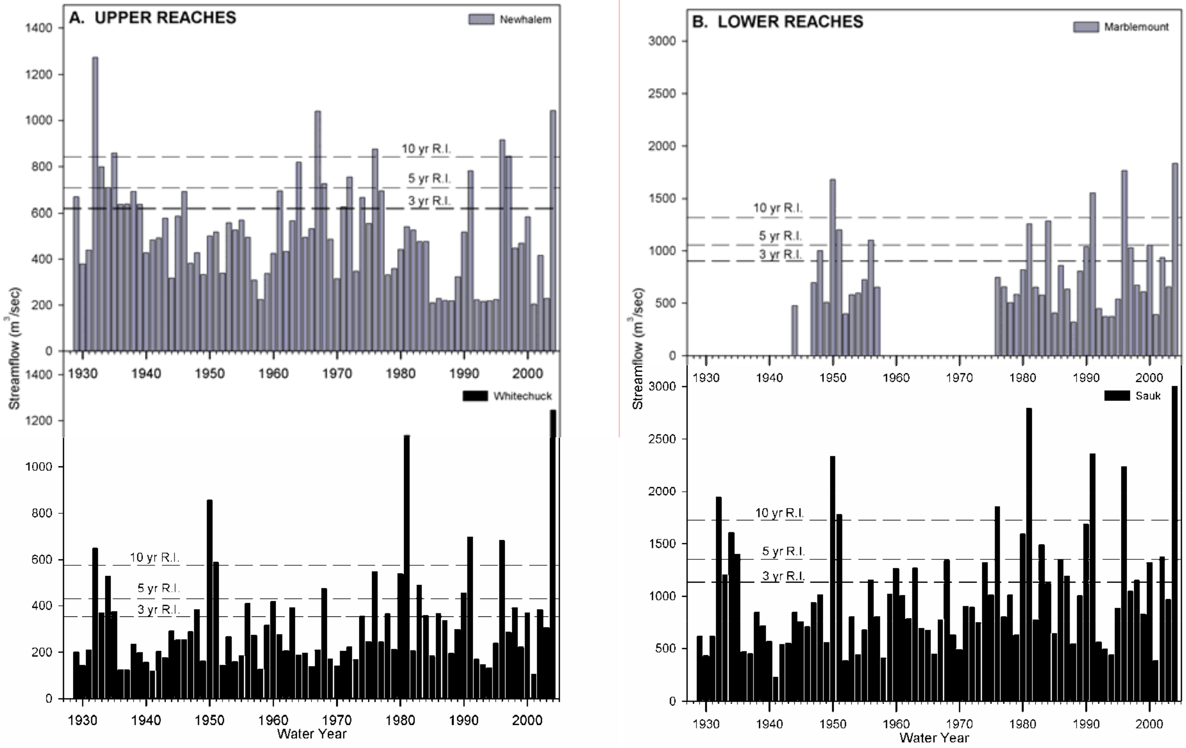


Figure 6. Average seasonal flows (1982-2002) normalized by drainage area. (USGS daily discharge data for the following gauges: A) Skagit River at Newhalem and the Sauk River above Whitechuck, B) Skagit River at Concrete, Skagit River at Marblemount and Sauk River at Sauk.)

area in the unregulated river. The annual hydrograph for the Whitechuck reach was similar to the historic hydrograph for Newhalem. The natural seasonal snowmelt peak begins in early April (~day 100), peaks in mid June (~day 165), and recedes gradually to summer base-flows in late August. Additionally, the Whitechuck reach shows increased intra-annual variation, in contrast to the fairly stable discharge of the Skagit at Newhalem.

The normalized pattern of average daily streamflow (1982-2002) for the Skagit River at Marblemount (USGS gauge 12181000, drainage area 3577km^2) contrasts with that of the Sauk River at Sauk (USGS gauge 12189500, drainage area 1849km^2) (Figure 6B). The Marblemount hydrograph incorporates both regulated flows from the main Skagit and discharge from unregulated tributaries including Newhalem Creek, Alma Creek and other small streams. Yet, intra-annual variation is minimal and there is no appreciable seasonal snowmelt peak, nor any winter rain peak. In contrast, the Sauk reach again shows two large seasonal peaks. The normalized discharge for the Skagit River at Concrete (USGS gage 12194000, drainage area 7089km^2) is intermediate to those of the Marblemount and Sauk reaches (Figure 6B). The seasonal flow pattern is attenuated, but similar to that of the Sauk River.



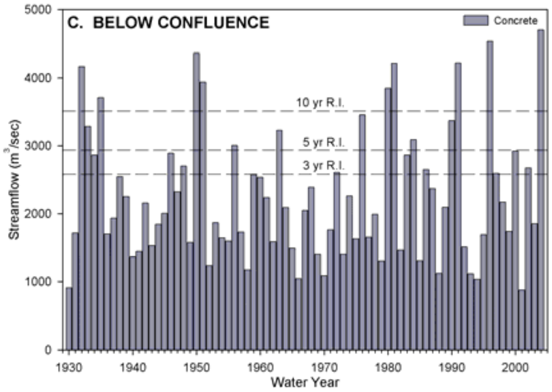


Figure 7. A comparison of annual peak flows in water years 1929-2004 for regulated (grey) and unregulated (black) reaches of the Skagit and Sauk Rivers. Three, five and ten-year flood return interval levels are indicated by dashed lines for the various reaches.

Annual Peak Flow

Annual peak discharge for Newhalem and Whitechuck from 1929-2004 are shown in Figure 7A. A comparison of these uppermost reaches reveals a higher discharge for the Newhalem reach; however, during extreme peak flow events (i.e. 1981, 2004) the discharge recorded on the upper Sauk River may equal or exceed that of the Skagit. Additionally, the incongruence of very large peak events (i.e. 1950, 1951 and 1981) between these two watersheds could result from flow regulation, differing weather patterns, or other watershed features.

Peak flows for the lower reaches of the Skagit and Sauk Rivers were similar to patterns observed in upper reaches (Figure 7B). Congruence between large peak flow events in 1950, 1951 and 1981 indicates that discharge from free-flowing tributaries of the Skagit River can offset some of the effects of regulation observed on the upper Skagit at Newhalem. Annual peak discharge for the Skagit River at Concrete (Figure 7C) was more congruent with the Sauk River than with the upper Skagit River.

Substrate Size Classes

Substrate data collected along study transects were classified into three size classes (Table 7). These classes include: 1) fine – sand and silt, 2) coarse – gravel, cobble, boulders and bedrock, and 3) duff – vegetative material. Observations were similar for both reaches of the Sauk River. Fines covered approximately 43% of the transect length, coarse material 33%, and duff the remaining 24%. On the Skagit River, substrate composition was similar in the Marblemount and Concrete reaches (70% fine, 15% coarse, and 15% duff). The Newhalem reach varied markedly from the other Skagit reaches (42% fines, 44% coarse, and 15% duff). The lack of fine sediment in this reach is likely a result of sediment trapping by the dams.

Table 7. Relative abundance of substrate size classes in each study reach. Values indicate the percent of the total transect length covered by each class. The fines category includes silt and sand. Coarse substrate includes gravel, cobble, boulders and bedrock. Duff is organic matter in various states of decay.

Stream Reach	Fines	Coarse	Duff
Newhalem	42	44	15
Marblemount	70	14	16
Whitechuck	45	33	22
Sauk	40	33	27
Concrete	69	18	13

Vegetation Structure

The relative cover of colonizing tree species varied between study reaches (Figure 8). Differences were more apparent in the upper reaches (Newhalem and Whitechuck), where the effects of flow regulation are more pronounced. The Newhalem reach had more mature cottonwood and alder than juvenile age classes, whereas the Whitechuck reach had more juvenile than mature trees (Figures 8 A, B). In the Marblemount reach, there were more juvenile cottonwood than red alder. On the Sauk reach, juvenile and mature cottonwoods were equally abundant, and red alder was represented by mostly mature trees. Cottonwood and alder was dominated by juvenile trees in the Concrete reach.

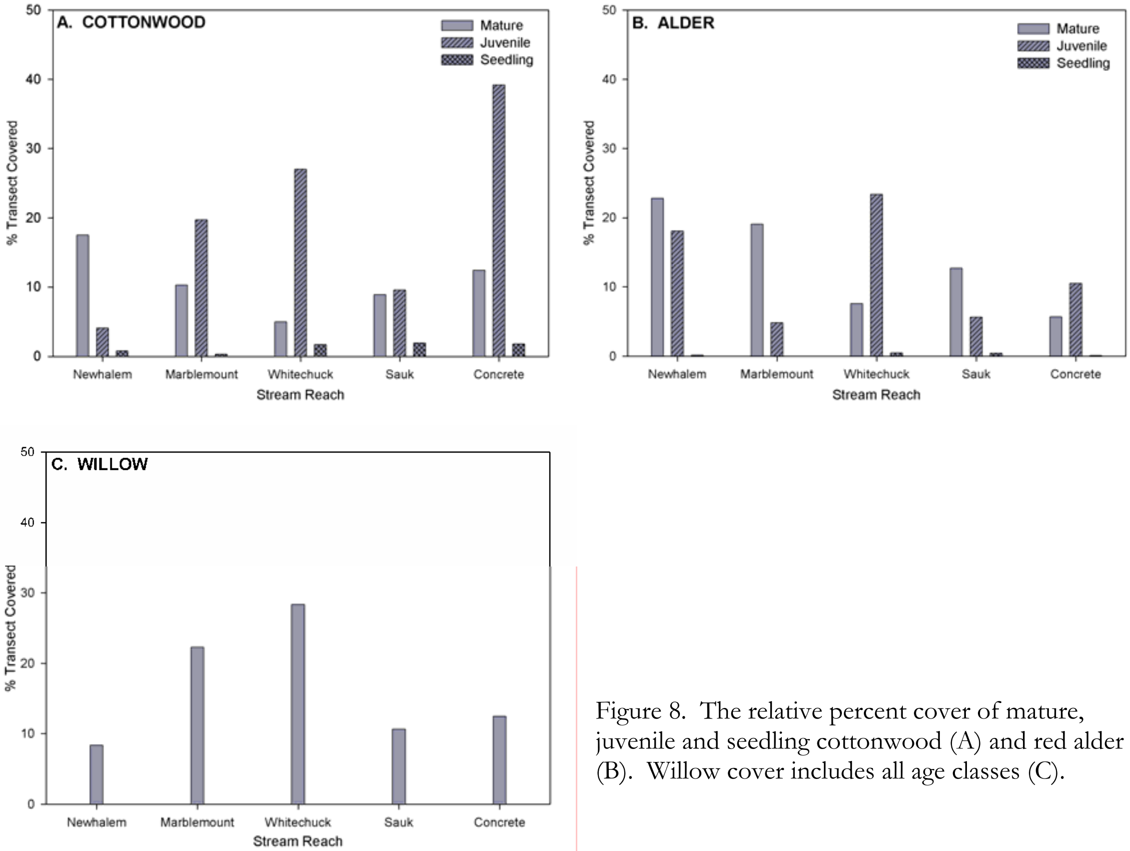


Figure 8. The relative percent cover of mature, juvenile and seedling cottonwood (A) and red alder (B). Willow cover includes all age classes (C).

Willow species could not be classified into age classes, due to their ability to readily sucker and sprout from the stump. Willow species were slightly more abundant on the Marblemount and Whitechuck reaches (>20%, Figure 8C), than on the other three reaches (8 to 12%).

Relative cover of late successional tree species including *Abies grandis*, *Acer macrophyllum*, *Pseudotsuga menziesii*, *Taxus brevifolia*, *Thuja plicata*, and *Tsuga heterophylla* was markedly higher in the uppermost reach of the Skagit (27.1% Newhalem) relative to all other reaches (4.8%

Marblemount, 2.3% Whitechuck, and 5.6% Sauk). The Concrete reach had only 1% cover of late successional trees.

There were marginal differences in the relative abundance of shrub species between reaches. The number of shrub species (total cover >0.1%) found on the Skagit River was 14 in both the Newhalem and Marblemount reaches and 13 on the Concrete reach, whereas on the Sauk River, 6 species were recorded in the Whitechuck reach and 10 in the Sauk reach. However, distribution of the two most common exotic shrubs in this region was different between study reaches. Himalayan blackberry (*Rubus discolor*) was only recorded on the Marblemount and Concrete reaches of the Skagit River, where it was found on all but one transect. Relative cover of Himalayan blackberry was 2.1% in the Marblemount reach and 8.4% in the Concrete reach. Scotchbroom (*Cytisus scoparius*) was found only in lower reaches, where it was common in the Marblemount (5.7% cover) and Sauk (4.1% cover) reaches and rare in the Concrete reach (0.4% cover).

The overall number of native forb species varied little between the Marblemount, Whitechuck, and Sauk reaches, but was lower in the Newhalem and Concrete reaches.

Table 8. Relative abundance of native and exotic forb species in each study reach. Herbaceous species present was recorded at 1m intervals along the length of transects and then summed for the entire study reach.

Stream Reach	**% Native Species Occurrence**	**% Exotic Species Occurrence**	**Number of Native Species Found**	**Number of Exotic Species Found**
Newhalem	81.48	18.52	8	3
Marblemount	58.59	41.41	11	15
Whitechuck	77.78	22.22	12	4
Sauk	97.79	2.21	11	3
Concrete	86.22	13.78	5	9

The number of exotic forb species recorded in the Newhalem, Whitechuck, and Sauk reaches was low compared to the Marblemount and Concrete reaches (Table 8). The percent occurrence of native and exotic forb species was approximately 80% native and 20% exotic on the Newhalem and Whitechuck reaches. Further, Marblemount had a higher percentage of exotic species (41.4% exotic) than the Sauk reach (2.2% exotic species). In contrast, the Concrete reach had more native than exotic species (86% native and 14% exotic).

Seedling Abundance and Distribution

Significant differences were exhibited in the abundance and distribution of seedlings between study reaches (Table 9). More cottonwoods were found in the Newhalem and Whitechuck reaches than the Marblemount and Sauk reaches. The elevational distribution of cottonwood seedlings differed between the Skagit and Sauk Rivers (Figure 9A). Approximately 75% of all seedlings recorded on the Skagit River

Table 9. Total number if seedlings observed in successive elevational bands (50-250cm) above mean base flow.

			Establishment Elevation (cm)				**Reach Total**
Reach	**Seedling Species**	**0-50**	**51-100**	**101-150**	**151-200**	**201-250**	
Newhalem	*Populus trichocarpa*	248	16	65	0	0	329
	Salix sp.	48	24	0	0	0	72
	Alnus rubra	14	32	7	0	0	53
Marblemount	*Populus trichocarpa*	110	37	3	0	0	150
	Salix sp.	387	45	0	0	0	432
	Alnus rubra	23	27	0	0	0	50
Whitechuck	*Populus trichocarpa*	82	101	22	1	0	206
	Salix sp.	32	393	94	0	0	519
	Alnus rubra	6	8	4	0	0	18
Sauk	*Populus trichocarpa*	19	22	11	4	7	63
	Salix sp.	32	225	190	124	138	709
	Alnus rubra	1	4	1	8	0	14
Concrete	*Populus trichocarpa*	333	114	42	77	2	568
	Salix sp.	108	24	1	0	0	133
	Alnus rubra	0	1	0	0	0	1

(above the confluence with the Sauk) were located at elevations less than 50cm above mean base flow. On the Sauk River, only 11% of all seedlings recorded were located below 50cm. The Concrete reach showed intermediary patterns with 60% of seedlings found between 0-50cm above base flow. The majority (70%) of seedlings on the Sauk River were found from 51-150cm above mean base flow water level.

Mann-Whitney Rank Sum tests showed significant differences (p=0.100) between the Newhalem and Whitechuck reaches for cottonwood seedlings in the 51-100cm elevational range and significant (p=0.002) differences between the Marblemount and Sauk reaches in the 0-50cm zone (Table 10). Highly significant differences (p<0.001) were also found between the Whitechuck and Sauk reaches of the Sauk River for both the 0-50 and 51-100cm elevational bands (Table 10). Significant differences were also found between

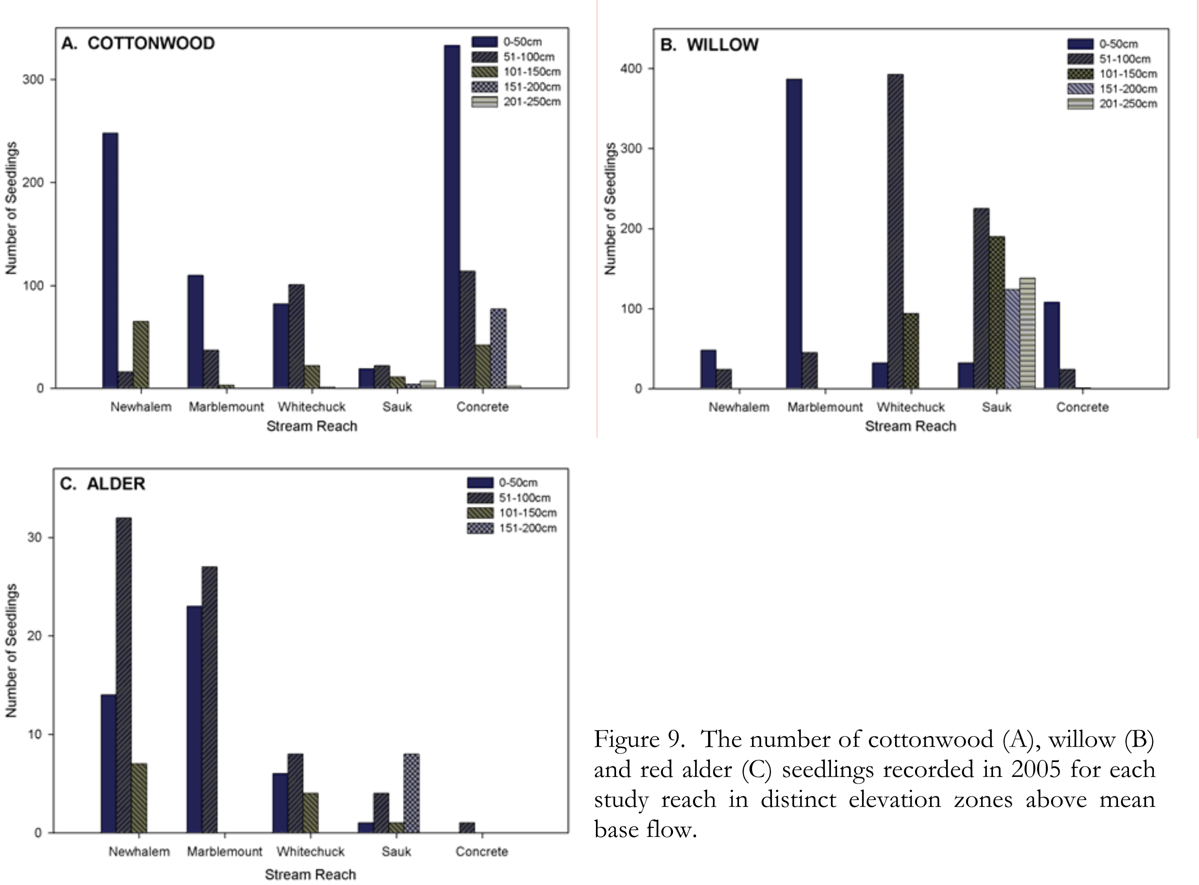


Figure 9. The number of cottonwood (A), willow (B) and red alder (C) seedlings recorded in 2005 for each study reach in distinct elevation zones above mean base flow.

Table 10. Results of Mann-Whitney Rank Sum tests on seedling abundance relative to elevation (0-50, 51-100, and 101-150cm) above the base flow water level.

Test	p-value	Test	p-value	Test	p-value
Cottonwood		**Willow**		**Red Alder**	
Newhalem x Whitechuck		*Newhalem x Whitechuck*		*Newhalem x Whitechuck*	
0-50	0.859	0-50 (t-test)	0.457	0-50 (t-test)	0.813
51-100	0.100*	51-100	0.083*	51-100	0.082*
101-150	0.315	101-150	NA	101-150	0.724
Marblemount x Sauk		*Marblemount x Sauk*		*Marblemount x Sauk*	
0-50	0.002**	0-50	<0.001**	0-50	NA
51-100	0.268	51-100	0.035**	51-100	0.245
101-150	0.501	101-150	NA	101-150	NA
Newhalem x Marblemount		*Newhalem x Marblemount*		*Newhalem x Marblemount*	
0-50	0.483	0-50	0.294	0-50	0.486
51-100	0.478	51-100	0.832	51-100	0.060*
101-150	NA	101-150	NA	101-150	NA
Whitechuck x Sauk		*Whitechuck x Sauk*		*Whitechuck x Sauk*	
0-50	<0.001**	0-50	0.082*	0-50	NA
51-100	<0.001**	51-100	0.424	51-100	0.730
101-150	0.927	101-150	NA	101-150	NA
Concrete x Newhalem		*Concrete x Newhalem*			
0-50	0.266	0-50	0.091*		
51-100	0.002**	51-100	0.915		
101-150	0.212	101-150	NA		
Concrete x Marblemount		*Concrete x Marblemount*			
0-50	0.739	0-50	<0.001**		
51-100	0.769	51-100	0.905		
101-150	0.496	101-150	NA		
Concrete x Whitechuck		*Concrete x Whitechuck*			
0-50	0.099*	0-50	0.134		
51-100	0.004**	51-100	0.046**		
101-150	0.301	101-150	NA		
Concrete x Sauk		*Concrete x Sauk*			
0-50	<0.001**	0-50	0.817		
51-100	0.426	51-100	0.061*		
101-150	0.955	101-150	NA		

*Significant at alpha = .10
**Significant at alpha = .05

Concrete and Whitechuck at the 0-50cm ($p=0.099$) and 51-100cm ($p=0.004$) ranges. Highly significant ($p<0.001$) differences were also found between Concrete and Sauk in the 0-50 zone. Chi-square analysis of a contingency table including counts for all reaches showed highly significant ($p<0.001$) differences in cottonwood seedling distribution between all stream reaches (Table 11).

Salix seedlings were more abundant than cottonwood seedlings in the Marblemount, Sauk, and Whitechuck reaches, yet less abundant than cottonwoods on the Newhalem and Concrete reaches. The Sauk River had more than two times as many willow seedlings as the Skagit River (Table 9). The majority of seedlings on the Skagit River were observed in the 0-50cm elevational band (Figure 9B). On the Marblemount reach, 90% of Salix seedlings were found below the 50cm elevation. On the Sauk River, less than 10% of Salix seedlings were found below 50cm with the greatest number of seedlings occurring in the 51-150cm zone.

Mann-Whitney Rank Sum tests showed significant ($p=0.083$) differences in willow seedling observations between the Newhalem and Whitechuck reaches in the 51-100cm range (Table 10). Additionally, significant differences were found between the Marblemount and Sauk reaches in both the 0-50cm range ($p<0.001$) and 51-100cm range ($p=0.035$). Differences ($p=0.082$) were also found between the Whitechuck and Sauk reaches at the lowest elevational band, but appear related to differences in seedling densities (Table 10). The Concrete reach also varied from Newhalem ($p=0.091$) and Marblemount ($p<0.001$) in the 0-50cm range, and from Whitechuck ($p=0.046$) and Sauk ($p=0.061$) in the 51-100cm elevational band. Chi-square analysis of a contingency table showed highly significant ($p<0.001$) differences between all study reaches (Table 12).

Table 11. Results of the Chi-square analysis on a contingency table of 2005 cottonwood seedling observations at discrete elevations above mean base flow water level in the five study reaches.

	Elevation Above Mean Base Flow (cm)				
Stream Reach	**0-50**	**51-100**	**101-150**	**151-200**	
Newhalem	248	16	65	0	$Chi^2 = 298$
Whitechuck	82	101	22	1	df = 12
Marblemount	110	38	0	0	alpha = 0.05
Sauk	19	22	11	4	power = 1
Concrete	333	114	42	77	p-value <0.001

Table 12. Results of the Chi-square analysis on a contingency table of 2005 willow seedling observations at discrete elevations above mean base flow water level in the five study reaches.

	Elevation Above Mean Base Flow (cm)					
Stream Reach	**0-50**	**51-100**	**101-150**	**151-200**	**201-250**	
Newhalem	48	24	0	0	0	$\text{Chi}^2 = 1724$
Whitechuck	32	393	94	0	0	df = 16
Marblemount	387	45	0	0	0	alpha = 0.05
Sauk	32	225	190	124	138	power = 1
Concrete	108	24	1	0	0	p-value <0.001

Red alder seedlings were less abundant than seedlings of cottonwood and willow; however, they were more prevalent on the Skagit River above the confluence than on the Sauk River (Figure 9C, Table 9). Only one alder seedling was recorded on the Skagit River below the Sauk confluence. Mann-Whitney Rank Sum tests showed significant (p=0.082) differences between Newhalem and Whitechuck in the 51-100cm range. Significant (p=0.06) differences were also seen between Newhalem and Marblemount at this elevation (Table 10). Chi-square analysis was not possible due to the small number of observations.

Overall trends in seedling elevation distribution were consistent for all three major riparian tree species. Recruitment on the Skagit River was primarily in the first 50cm above base flow water level and rarely occurred above 100cm. The majority of seedling recruitment on the Sauk River occurred above 50cm and often up to 250cm above base flow. The Concrete reach showed intermediary results with 59% of cottonwood seedlings occurring between 0-50cm above mean base flow. Seedling densities were highly variable for all stream reaches due to differences in floodplain geomorphology, with the highest densities on fine sediments.

Age Distribution

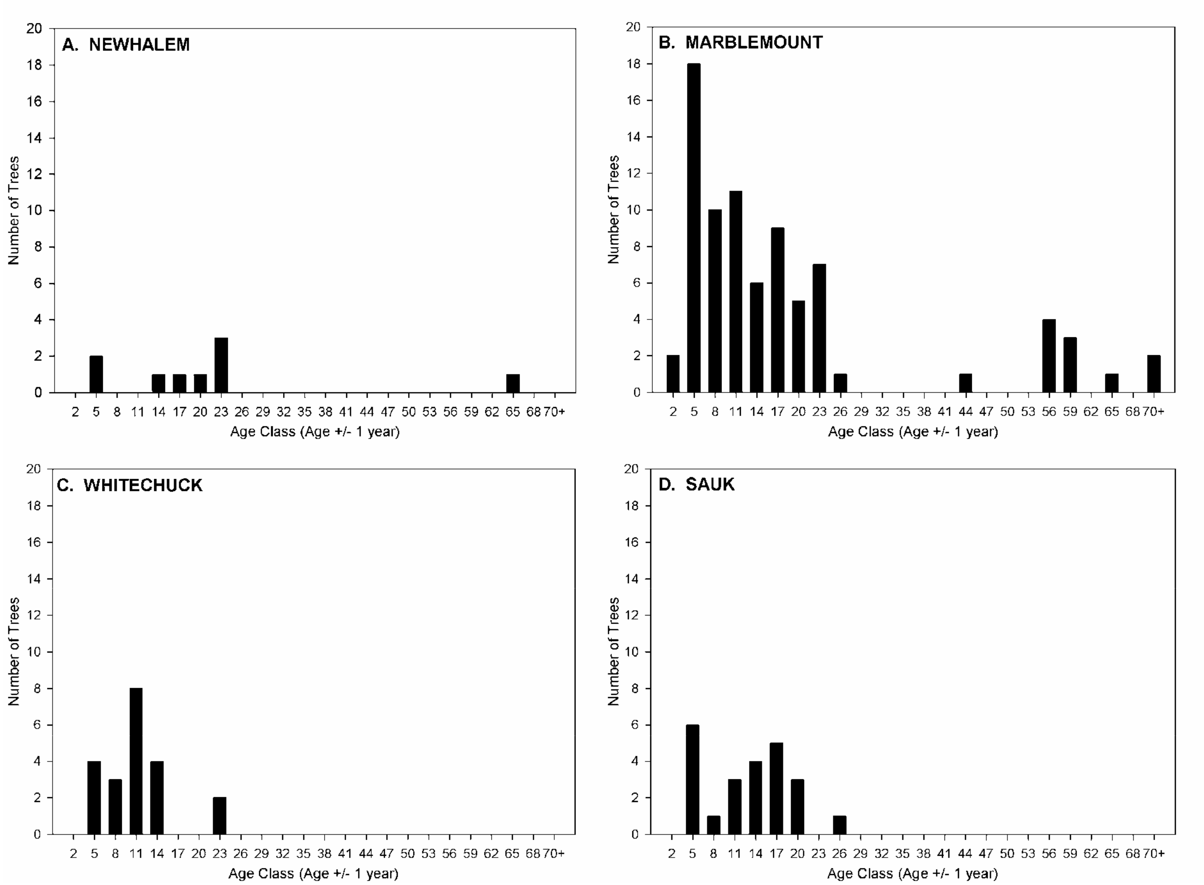
A total of 294 cottonwood, alder, and willow trees were aged over the entire study area. As the primary focal species of this project, cottonwoods comprised the majority (206) of trees aged; totals by reach are presented in Table 13. The number of cottonwood age classes varied between study reaches (Figure 10). Six distinct age classes of cotton-woods were found in the Newhalem reach of the Skagit and five on the Whitechuck

Table 13. The total number of cottonwood trees aged from cores or trunk cross-sections in each study reach. Age classes are defined by a three-year interval.

Stream Reach	Number of Trees Aged	Number of Age Classes	Age Range (yrs)
Newhalem	11	6	6-65
Whitechuck	72	14	3-92
Marblemount	23	5	4-23
Sauk	24	7	4-25
Concrete	76	11	4-45

reach of the Sauk River. A Mann-Whitney rank sum test showed the ages present were significantly ($p=0.025$) different between the two reaches. Due to the difficulties in accurately aging cottonwood trees, age classes were grouped into three year age spans (i.e. age class 5 is trees 4-6 years old). On the Newhalem reach, cottonwoods were older and the age classes included 5, 14, 17, 20, 23 and 65, whereas age classes on the Whitechuck reach included: 5, 8, 11, 14 and 23 (Figures 10 A, C). Fourteen distinct age classes were found on the Marblemount reach: 2, 5, 8, 11, 14, 17, 20, 23, 26, 44, 56, 59, 65 and 70^+ (Figure 10B). On the Sauk reach, seven age classes were identified: 5, 8, 11, 14, 17, 20 and 26 (Figure 10B). Eleven age classes of cottonwood (5, 8, 11, 14, 17, 20, 23, 26, 29, 35 and 44) were observed on the Concrete reach (Figure 10E).

The relationship between age and size (i.e. trunk diameter) was explored for cottonwoods (<40 years old) using linear and polynomial regression. After transforming the data to meet the assumptions of normality and constant variance for regression, the relationship between age and trunk diameter was linear ($R^2=.716$, $p<0.001$) for trees on the Skagit River above the confluence. On the Sauk River both the linear and third order polynomial curves were significant ($p<0.001$). While the linear relationship had a higher F statistic ($F=106.924$) than the polynomial regression ($F=42.980$), the polynomial had a slightly higher R^2 value ($R^2_{linear}=.748$, $R^2_{polynomial}=.791$) and makes more ecological sense. A linear relationship between age and size would not be expected to persist as the tree matures. The Skagit River below the confluence also showed a third order polynomial relationship ($R^2=.836$, $p<0.001$) between age and trunk diameter. Overall, there were small differences in the growth rate of cottonwoods between the various study reaches; however, ANOVA showed these differences were not significant.



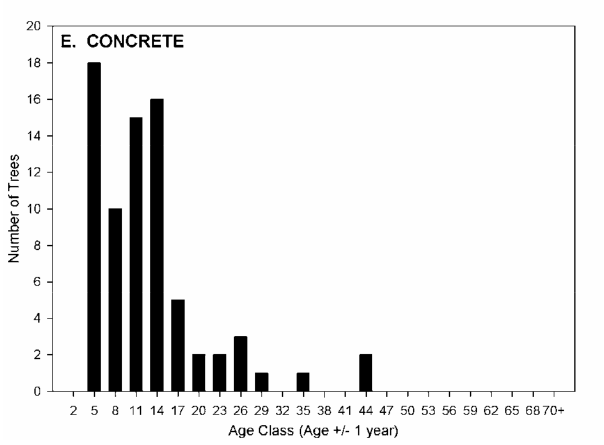


Figure 10. Number of cottonwood trees recorded in each age class (±1 year) for the five study reaches. The data was derived from tree cores and trunk cross-sections collected in 2004 and 2005.

Recruitment Box Model (RBM)

Given the temporal constraints of the tree core data, the RBM analysis was limited to flow data from 1980 to 2001. A comparison of overall scores and observed recruitment data for each year in the regulated, unregulated and partially-regulated reaches are presented in Table 14. Scoring for individual criteria is presented in Appendix D. Recruitment box overlays were also created for two years in each reach to illustrate favorable and unfavorable flow patterns with regard to timing and recession of river stage (Figure 11).

In the regulated reach (Marblemount gauge), the model predicted recruitment for 10 of the 22 years analyzed (Table 14, Figure 12A). Age data collected on cottonwoods in this reach indicated higher recruitment in 8 of the 10 years predicted by the model. Conversely, the model predicted the remaining 12 years would have been unfavorable for cottonwood recruitment. Field data showed only 5 of those 12 years had low recruitment. Overall the model was correct in predicting favorable and unfavorable years for cottonwood recruitment 59% of the time.

Table 14. Total scores from the application of the Recruitment Box Model criteria to annual hydrographs from 1980-2001 in each study segment. In years with total scores≥4, the model predicted successful cottonwood recruitment. Observed recruitment data was derived from tree core and trunk cross-section age data collected in each reach.

	Regulated			**Unregulated**			**Partially-Regulated**		
Year	Score	Predicted	Observed	Score	Predicted	Observed	Score	Predicted	Observed
1980	1	No	No	3.66	No	No	2.50	No	No
1981	4.66	Yes	Yes	3.66	No	No	4	Yes	No
1982	5.66	Yes	Yes	4	Yes	No	3	No	No
1983	2	No	No	3	No	No	2	No	No
1984	4.66	Yes	No	6	Yes	No	5.16	Yes	No
1985	2.66	No	No	4	Yes	Yes	3.66	No	No
1986	5	Yes	Yes	3.66	No	No	2.83	No	No
1987	5	Yes	Yes	5.66	Yes	Yes	3.50	No	No
1988	2	No	Yes	3.33	No	No	3	No	No
1989	1	No	Yes	3	No	No	3	No	No
1990	2.33	No	Yes	3.66	No	No	2.16	No	Yes
1991	7	Yes	No	5	Yes	Yes	4	Yes	Yes
1992	5	Yes	Yes	4	Yes	Yes	7.5	Yes	Yes
1993	4	Yes	Yes	6	Yes	Yes	5	Yes	Yes
1994	1	No	Yes	4	Yes	Yes	4	Yes	Yes
1995	2	No	No	3	No	Yes	3	No	No
1996	3	No	No	4	Yes	Yes	3	No	No
1997	7	Yes	Yes	5	Yes	No	6.50	Yes	Yes
1998	2	No	Yes	4	Yes	No	4	Yes	Yes
1999	3	No	Yes	4	Yes	Yes	3	No	Yes
2000	4.66	Yes	Yes	5.33	Yes	Yes	5.66	Yes	Yes
2001	2.66	No	Yes	3	No	Yes	2.66	No	No

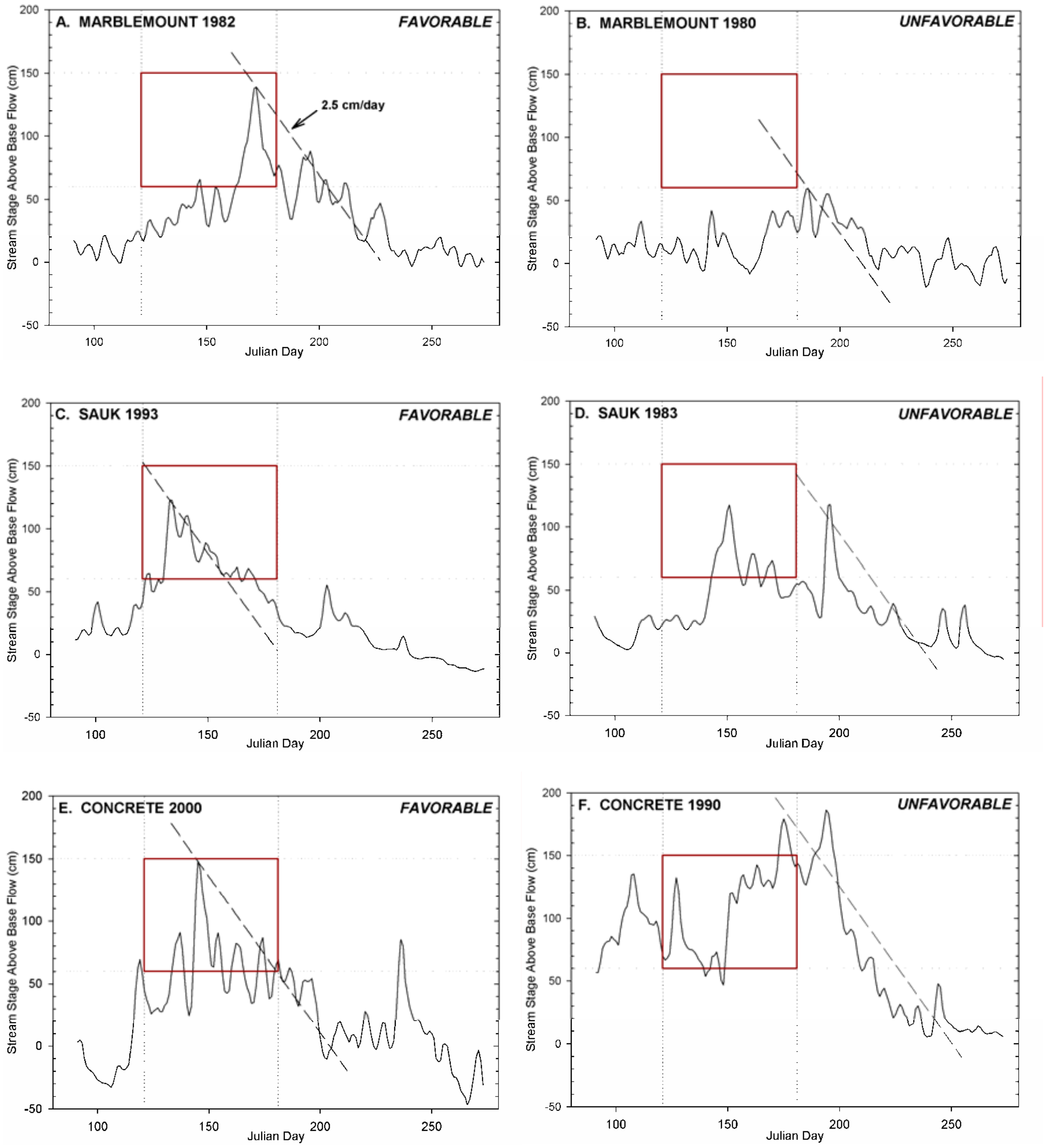


Figure 11. A comparison of criteria 2 (timing) and 3 (stage recession rate) results of the recruitment box analysis to seasonal flow patterns for regulated (A, B), unregulated (C, D) and partially-regulated (E, F) river reaches in years favorable and unfavorable for cottonwood seedling establishment. The vertical dimension of the box represents the optimal seedling establishment elevation of 60-150cm above mean base flow. The horizontal dimension of the box represents the main period of cottonwood seed release (May 1-June 30). The dashed line indicates the ideal stage recession rate of 2.5 cm/day.

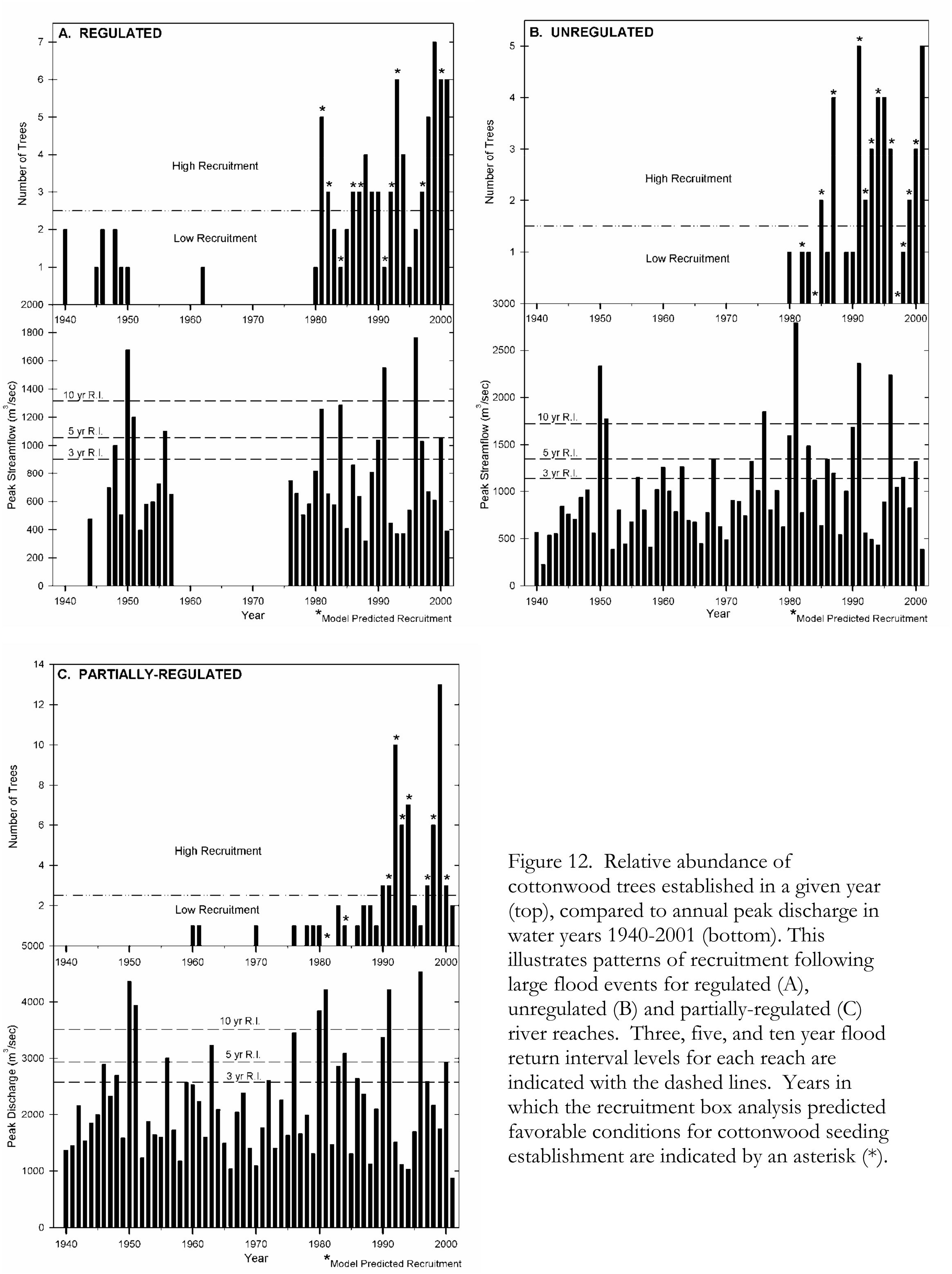


Figure 12. Relative abundance of cottonwood trees established in a given year (top), compared to annual peak discharge in water years 1940-2001 (bottom). This illustrates patterns of recruitment following large flood events for regulated (A), unregulated (B) and partially-regulated (C) river reaches. Three, five, and ten year flood return interval levels for each reach are indicated with the dashed lines. Years in which the recruitment box analysis predicted favorable conditions for cottonwood seeding establishment are indicated by an asterisk (*).

Timing and stage of the seasonal peak are critical factors limiting seedling recruitment in the regulated reach. Both the timing and stage of the seasonal peak were favorable in only 3 of the 22 years analyzed. In the majority of years, the river stage did not rise to >60cm above base flow, indicating seedling establishment would occur at lower elevations on the floodplain. The RBM overlay for Marblemount in 1982 (Figure 11A) illustrates a favorable flow pattern in this reach. While the peak does occur late, it is still within the period of seed release. Seeds released after the peak would have the greatest chance of survival. The stage recession rate is highly variable but on average favorable. The RBM overlay for Marblemount in 1980 (Figure 11B) illustrates a typical flow pattern found in this reach. The peak occurs after the period of seed release and does not raise stream stage to >60cm above base flow. In this year, seedlings would establish near mean base flow and could subsequently be scoured by moderate winter flows.

Cottonwood recruitment on the unregulated reach (Sauk gauge) was predicted by the model in 13 of the 22 years analyzed (Table 14, Figure 12B). Field observations showed high levels of recruitment in 9 of the 13 years predicted. Field data also indicated little or no cottonwood recruitment in 7 of the 9 years predicted to be unfavorable for recruitment. The overall accuracy of model predictions in the unregulated reach was 73%.

In contrast to the regulated reach, the unregulated reach showed favorable timing, stage elevation and recession rates in 19 of the 22 years analyzed. Unfavorable conditions for cottonwood recruitment were predominately created by large scour flows on this reach. In 16 of the 22 years, a large scour flow (greater than the peak associated with seedling establishment) occurred less than one year after seedling establishment.

The RBM overlay for the unregulated reach (Sauk 1993, Figure 11C) demonstrates highly favorable conditions for cottonwood seedling establishment. The seasonal peak occurs early during the period of seed release raising the stage of the river >60cm above base flow and subsequently recedes to base flow at a rate of less than 2.5 cm/day. Seeds produced during a majority of the release period would have the opportunity to germinate at optimal elevations and maintain root contact with declining soil moisture throughout the summer, increasing their likelihood of survival. The 1983 Sauk hydrograph (Figure 11D) illustrates unfavorable conditions arising from a scouring peak in late summer. Seedlings already established at elevations <120cm were likely to be scoured by the second peak flow event.

In the partially-regulated reach (Concrete gauge), the RBM predicted cottonwood recruitment in 9 of the 22 years, and 7 of these coincided with recruitment pulses observed in the field data (Table 14, Figure 12C). Eleven of the 13 years predicted by the model to be unfavorable for recruitment, showed little or no recruitment in field data. Thus, the model's predictions coincided with observed data in this reach 82% if the time.

The partially-regulated reach had intermediate flow patterns to the other reaches. Timing, stage recession rates, and scour flows were all important factors in determining favorable years for recruitment. Favorable peak flow timing and stage recession rates occurred in 8 years on this reach, compared to 3 years in the regulated (Marblemount) and 19 years in the unregulated (Sauk) reach. The partially regulated reach also had an intermediate number of years in which scour flows lead to unfavorable seedling recruitment conditions.

RBM overlays illustrate the variability of flow patterns in the partially regulated reach. The Concrete hydrograph for 2000 (Figure 11E) shows a common pattern seen in this reach. In general, the seasonal peak was not clearly defined and stage recession rates were highly variable. The RMB overlay in 1990 (Figure 11F) demonstrates several flow pattern elements that would be unfavorable to cottonwood seedling establishment. During the first half of the seed release period, seedlings would have the opportunity to establish in the optimal elevation band; however, during the second half of the release period those seedlings would have been scoured out by a later flow peak. Additionally, those seeds released later would establish at elevations >150cm above base flow leaving them more susceptible to desiccation in late August and early September.

DISCUSSION

Seasonal Flow Patterns

Analyses of peak and seasonal flow patterns clearly show several alterations to the Skagit River's natural flow regime. These effects are most prominent just downstream of the last dam (Newhalem reach) and diminish as the distance below the dam increases. Many of these alterations to seasonal flow patterns, and their subsequent effects on cottonwoods, have been studied on other rivers in the western U.S. and Canada. Studies along the Willamette River in Oregon (Dykaar and Wigington 2000, Fierke and Kauffman 2005), the Red Deer River in Alberta (Cordes et al. 1997), and the Kootenai River in British Columbia and Montana (Polzin and Rood 2000) have documented reductions in black cottonwood regeneration due to flow regulation. By comparing our findings to these studies, we feel the Skagit River flow regime limits regeneration of black cottonwood in the reach just below the SCL dams.

The observed decrease in the magnitude of the seasonal snowmelt peak reduces the river's ability to scour vegetation, transport sediment and inundate floodplain soils, as well as, deposit seeds at appropriate elevations for establishment (Cordes et al. 1997, Polzin and Rood 2000). The delayed timing of the snowmelt peak also conflicts with seed dispersal by black cottonwood (Rood and Mahoney 1998). Finally, the decrease in intra-annual variation reduces the likelihood of recruitment at varying elevations on the floodplain, altering floodplain forest structure. Collectively, these flow alterations conflict with cottonwood phenology and lower the probability of successful seedling recruitment along the Skagit River (Rood and Mahoney 1990, 1998, Dykaar and Wigington 2000).

The most serious threat facing black cottonwood along the Skagit River is the lack of successful regeneration in the reach just below the dams. Regeneration is primarily limited by alterations to the flow regime in the late spring and early summer months. Drought mortality does not appear to be a significant factor in seedling recruitment. Similar to observations made by Polzin and Rood (2005) on the Elk River, British Columbia. The risk of late summer drought mortality is reduced along the Skagit River by the slight augmentation of late summer base flow levels and the presence of sporadic rain events throughout the summer months.

Patterns of Vegetation Distribution

The observed patterns of vegetation distribution on the Skagit River further strengthen our conclusion that flow regulation has altered the floodplain forest structure below the dams. The regulated reach directly below the dams was dominated by mature trees, both cottonwood and red alder, whereas free-flowing reaches along the Sauk River were dominated by multiple age classes of juvenile trees. Additionally, later seral stage species were more common in the uppermost regulated reach. These patterns are similar to those reported by Polzin and Rood (2000) on the Kootenai River. They reported a marked decline in the occurrence of juvenile age classes of cottonwoods below Libby Dam, in addition to the occurrence of pines, firs, larches, and junipers in the riparian zone of regulated reaches.

Members of the Salicaceae plant family dominate most active floodplain areas in northern temperate climates, due to numerous life history traits that allow them to thrive in response to fluvial disturbances (Braatne et al. 1996, Karrenberg et al. 2002). Characteristics commonly found in cottonwood and willow species include: tolerance to inundation and sedimentation, flexible stems and branches that bend in fast flowing water, deep anchoring root systems, production of adventitious roots, root suckering, and the ability to regenerate from branch fragments. These traits allow cottonwood and willow to survive where other species cannot. In areas with less disturbance, cottonwoods and willows are often out competed by other species (Karrenberg et al. 2002). The variable abundance of cottonwoods and willows in regulated and unregulated reaches gives insight into the degree of fluvial disturbance. The uppermost reach of the Skagit River had fewer willows and cottonwoods than the upper reach of the free-flowing Sauk River. This observation indicates lower levels of fluvial disturbance and a less dynamic floodplain surface in the regulated reach despite the fact that this reach has higher discharge.

The effects of sediment trapping behind flow regulation structures are well documented (Rood and Mahoney 1990, Polzin and Rood 2000, Nilsson and Berggren 2000, Shafroth et al. 2002). Fine sediments retain moisture longer, allowing slower stage recession rates that are more favorable for cottonwood and willow seedling survival. Substrate size class data and the relatively small number of willows and juvenile cottonwoods in the Newhalem reach of the Skagit River, compared to the Whitechuck reach of the Sauk River, confirm that dams are limiting the supply of fine sediment. This lack of sediment reduces the ability of cottonwood and willow species to regenerate.

The relative abundance and distribution of the three colonizing floodplain species (cottonwood, willow, and red alder) also differed among the lower river reaches. Contributions of flow and sediment from tributaries appear to be a major factor responsible for these differences. Discharge in the Sauk reach is augmented by the Whitechuck and Suiattle Rivers and other smaller tributaries, increasing the mean annual discharge by nearly three times. The Marblemount reach of the Skagit River is augmented to a lesser extent by the Cascade River, Alma creek, and other smaller streams. The increased occurrence of willows and juvenile cottonwoods on the Marblemount reach (compared to the Newhalem reach) appear related to discharge and sediment inputs by these tributaries. The coinciding decrease in willows and juvenile cottonwoods on the lower Sauk reach, compared to the Whitechuck reach, appears related to the major flood event that occurred in November 2003. This was the largest flood ever recorded for the Sauk River (~100yr flood), with extensive scour and sedimentation throughout the reach (Figure 13). These flood-related impacts were far less dramatic on the Marblemount reach of the Skagit River due to flow dampening by the Skagit River dams (~40 year flood).

Figure 13. Effects of the 2003 flood on the Sauk River.

There was little variation between native and exotic forb distribution patterns on the uppermost reaches, whereas strong differences appeared between lower regulated (Marblemount) and non-regulated (Sauk) reaches. The incidence of exotic forbs was highest in the Marblemount reach and lowest in the Sauk reach. The low incidence of exotics on the Sauk may also be related to the 2003 flood. Exotic species are typically not well adapted to the effects of flooding and would be more susceptible to scour or sedimentation (Drs. Reinhard Steller, Jeffrey H. Braatne pers com.). The number of exotic forb species was intermediate on the Concrete reach compared to the upper reaches; however, Japanese Knotweed (*Polygonum cuspidatum*), a highly invasive exotic species, was found only in the Concrete reach.

The most significant differences between study reaches were found in seedling abundance and distribution. On the Skagit River, cottonwood and willow seedlings were located less than 50cm above base flow. This location has a profound impact on seedling survival. Previous studies have repeatedly shown that 60-150cm above base flow is the "optimal" elevation for seedling establishment to avoid death by desiccation, scour or excessive sedimentation (Braatne et al. 1996, Rood and Mahoney 1998, Polzin and Rood 2005). The recruitment box analysis revealed that this recruitment at low elevations was the result of the dampening of the seasonal peak by the dams. Many cottonwood seeds are dispersed by the river and are deposited on fresh sediment as the water levels recede. If the river stage remains low throughout the period of seed release, seeds are less likely to be deposited at higher elevations and are thus highly susceptible to scour by winter flows. Repeated recruitment at low elevations followed by scour has been observed on other flow-regulated rivers (Scott et al. 1997, Johnson 2000). An increase in seasonal discharge would diversify seedling distribution patterns and increase seedling survival on the Skagit River.

The varying abundance of red alder and willow seedlings on the Skagit and Sauk Rivers reflects the differing disturbance regimes and seasonal flow patterns between regulated and unregulated rivers. The large numbers of willow seedlings combined with the small number of red alders on the unregulated Sauk River contrast sharply with results seen on regulated reaches along the Skagit River. Lower levels of disturbance on the upper Skagit combined with red alder seed dispersal traits would explain these patterns because red alder release their seeds over the late fall and winter months making them less dependent on spring and summer flow patterns for dispersal and establishment.

Recruitment Box Model

Using the Recruitment Box Model (RBM), we were able enumerate specific aspects of the Skagit River flow regime that were less favorable to the recruitment of cottonwood. The theoretical background for this model has been validated by its successful use in restoration efforts on the St Mary's River, Alberta (Rood and Mahoney 2000) and the Truckee River, NV (Rood et al. 2003). In this project we modified the RBM slightly to account for climatic differences and the different seasonal flow patterns of a mesic coastal river.

RBM analysis led to several notable observations for the Skagit River. In particular, the largest increases in seedling recruitment generally occurred 2-4 years after large flow events (Figures 13A-C). This temporal disjunct between disturbance and recruitment is not generally found in semi-arid systems. In a dry climate, the disturbance flow must scour vegetation to provide suitable seedling establishment sites, and also inundate the floodplain to provide the water needed for successful seedling establishment. Therefore, a pulse of recruitment is observed in the same year as large disturbance events and continued influence of that event is limited (Braatne et al. 1996, Cordes et al. 1997, Johnson 2000). On both the Skagit and Sauk Rivers, we observed high levels of recruitment up to five years following large disturbance flows. This pattern of continued recruitment following large flow events has been reported in other studies (Scott et al. 1997, Rood et al. 1998, 1999, Samuelson and Rood 2004, Polzin and Rood 2005). Thus, winter storm peaks provide the physical scour needed to create nursery sites, with spring peaks inundating and moistening floodplain soils. This led to a temporal separation between physical disturbance flows, floodplain inundation, and seedling recruitment.

Our RBM analysis spanned 22 years (1980-2001), during which there were four major flood events (water years: 1980-81, 1983-4, 1990-1 and 1996). On the upper Skagit River these were followed by four recruitment pluses, where as the Sauk River had three pulses in recruitment and the Skagit River below the confluence had only two. It should be noted that the bulk of recruitment data for the Skagit River, above the confluence, was collected in the Marblemount reach, with only 9 of the 86 trees shown in Figure 10 located in the Newhalem reach. This inconsistency in recruitment between the Newhalem and Marblemount reaches indicates a substantial increase in successful recruitment as the distance below the dams increases and influences from unregulated tributaries are more prevalent. Additionally, flood-dampening by the SCL dams dramatically reduces scour flows on Skagit River, above the confluence, leading to higher recruitment in the Marblemount reach.

Analysis on the timing of the seasonal peak illustrated one of the major alterations to the natural flow regime found on the Skagit River. In 12 of the 22 years covered by the analysis, the seasonal peak in the regulated reach occurred after the period of seed release (May 1 to June 30). This delay in timing conflicts with cottonwood phenology. Cotton-woods require a peak flow during seed release to inundate nursery sites and disperse seeds (Mahoney and Rood 1998). Additionally, higher flows in the late summer could scour seedlings established at lower elevations during the period of seed release (Braatne et al. 2006). In contrast, the seasonal peak occurred between May 1 and June 30 in all but three years on the unregulated Sauk River. The partially-regulated reach of the Skagit, below the confluence, showed intermediate flow patterns. In this reach the timing of the seasonal peak was favorable in 16 of the 22 years spanned by the analysis.

RBM analysis showed recession rates were gradual (generally 1-2 cm/day) on the upper Skagit River, but river stage was seldom raised to 60cm above base flow during the seasonal peak. In 12 of the 22 years examined, river stage did not meet the minimum stage increase of 60cm above base flow. This would lead to the establishment of seedlings at lower than optimal elevations on the floodplain. In contrast, the Sauk River exceeded this minimum stage elevation every year and had favorable recession rates, which led to seedling establishment over a wider range of elevations. Higher stage increases (up to 350cm above base flow) were observed on the Skagit River below the confluence along with rapid recession rates. Frequently, recession rates >10 cm/day were calculated for this reach resulting in unfavorable conditions for seedling establishment. Rapid declines in discharge and increased stage recession rates in late summer may cause newly established seedlings to desiccate as roots lose contact with the capillary fringe (Amlin and Rood 2002). Seedling data collected in 2005 corresponded with these predicted patterns in each reach. Seedlings were primarily located at low elevations in the regulated reach, at optimal elevations in the unregulated reach, and were less abundant on the partially-regulated reach.

Drought induced mortality appears less important in western Washington than in more arid systems, due to relatively milder summer temperatures and frequent rain events during the growing season. However, low flows in August (the hottest and driest month on the Skagit) could lower seedling survival. There is some inconsistency in previous research as to the minimum flow required for seedling survival. Average August discharge prior to flow regulation has been used in other studies (Braatne et al. 2006); however, these data were unavailable for the gauges used in the analysis. In this study the seven day, ten year low flow average ($Q_{7,10}$) was used as the minimum August flow. $Q_{7,10}$ is also a common measure used by many regulatory agencies and equates approximately to 85% exceedence flow on these rivers. Since base flow is typically not reached until late August or early September when the days shorten and temperatures begin to cool, there was little threat of drought mortality in most years.

In the Skagit River basin, scour related to winter storms is an important factor in seedling survival. Even when all aspects of the flow regime are favorable to seedling establishment, a large winter storm peak could remove most of the newly establish plants. Several studies have shown that seedlings are highly susceptible to scour in the first two years after establishment (Rood and Mahoney 1990, Scott et al. 1997). Winter scour was found to be the overriding factor in many years. On the Sauk River, there was not one year in which a scour flood greater than the seasonal peak of the recruitment year did not occur within two years post establishment. Thus, only 6 of the 22 years analyzed were somewhat favorable in regard to scour flows on the Sauk River. On the upper Skagit River, the flood dampening effects of the dams were evident in that 8 years were somewhat favorable and 2 years highly favorable with regard to scour flows. This would also explain why we observed more recruitment pulses on the Marblemount reach than on the Sauk River.

Overall, the RBM predictions aligned more closely to field observations of recruitment in the unregulated and partially-regulated river reaches than in the regulated reach. The reduced accuracy of model predictions in the regulated reach may be the result of gauge location. The gauge choice for the Skagit above the confluence was not ideal; however, it was the only gauge available. The gauge at Marblemount is above the Cascade River tributary and, therefore, does not include the additional discharge from this system; however, the majority of trees sampled in that reach were located below this tributary. Additionally, the use of a generalized rating curve gives only an approximation of changes in river stage; however, the relatively coarse scale of this analysis allows for the use of such an approximation. Climatic factors not included in the model such as extreme heat or frost that can kill seedlings could also influence results.

CONCLUSIONS

The results of this study reinforce the accuracy and efficacy of the Recruitment Box Model. With minor alterations for climatic and inter-specific differences, the RBM can be effectively applied to coastal rivers in western Washington to evaluate cottonwood population sustainability. The addition of one or more climatic criteria (i.e. average August precipitation and temperature) to the model could further increase its accuracy. Finer scale application of the RBM could also be expanded with the use of LiDAR to obtain highly accurate floodplain topography measurements.

Based on the results of this analysis, two flow alterations could be made to the Skagit River to promote cottonwood recruitment in the upper reach of the Skagit just below the dams. First, the magnitude of the seasonal peak should be increased to raise the stage of the river to a level of 60-150cm above base flow. Second, the timing of the seasonal peak should be adjusted to fall within the period of seed release. Our analysis showed the peak is too small to increase river stage above 60cm, and typically occurs late in the summer, resulting in reduced cottonwood recruitment in the Newhalem reach. It is also important to remember that the conditions favorable to cottonwood recruitment are not met every year. Even in a natural system, cottonwood recruitment occurs on average every 5-10 years (Bradley and Smith 1986, Stromberg et al. 1991, Scott et al. 1996, 1997).

Several differences between the Skagit and Sauk Rivers were documented in this study that would warrant further research. First, the effects of the 2003 flood including changes in vegetation patterns, vegetative cover and channel migration could be analyzed using historic and current aerial photography or satellite imagery. Additionally, further study of seedling establishment and survival rates should be conducted as this is the key to sustaining a viable floodplain forest along the Skagit River.

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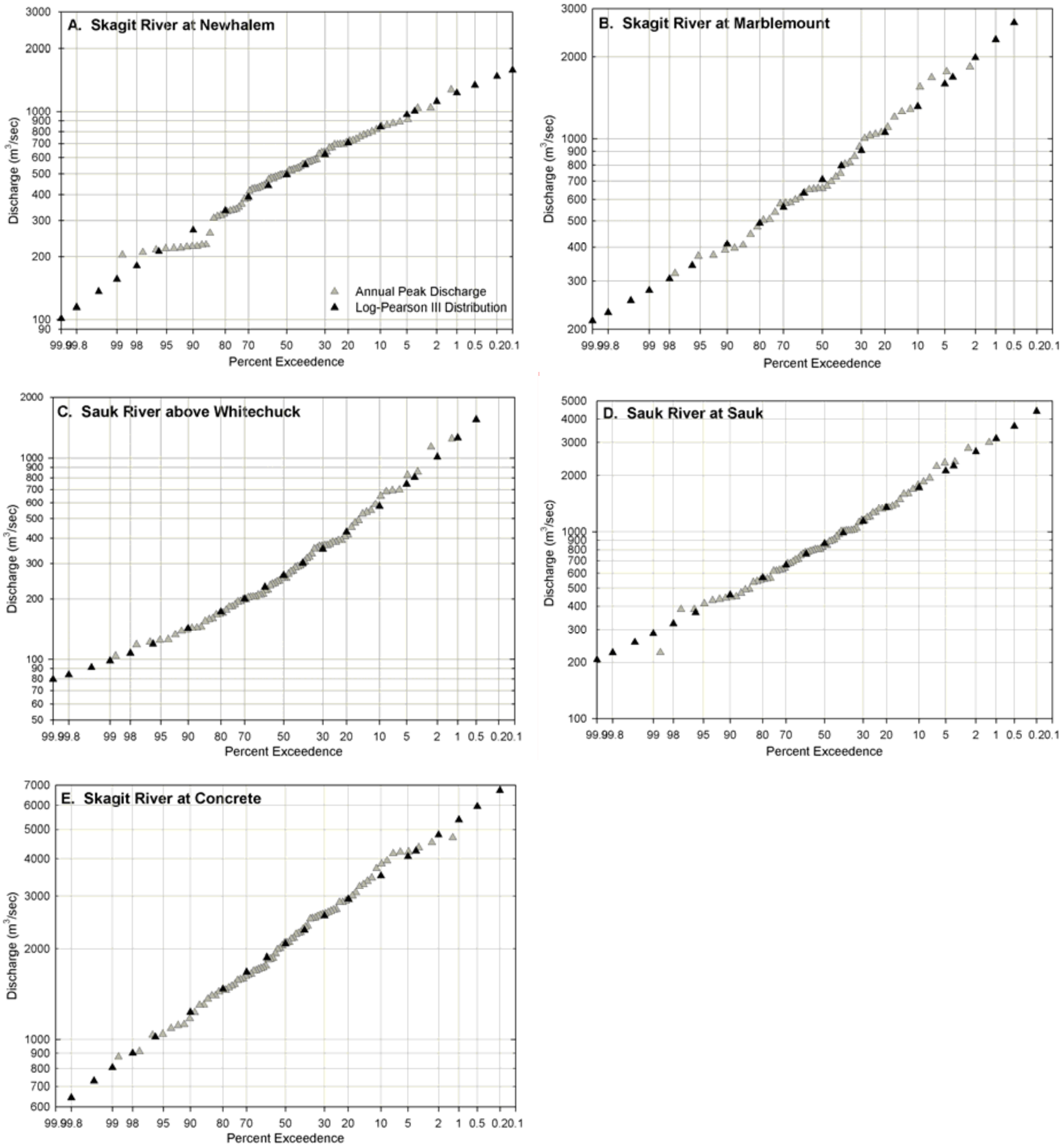
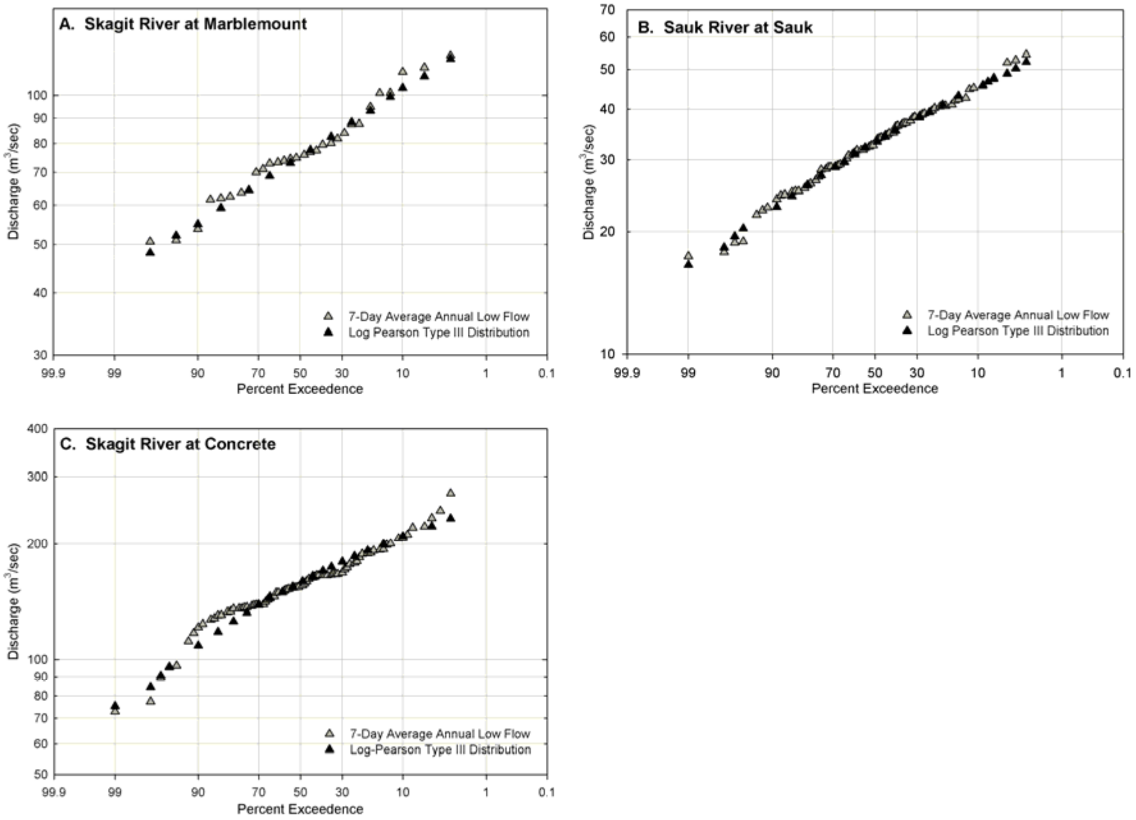
Appendix A. Complete list of all plant species recorded in the study area. Plant identifications were made with reference to Hitchock and Cronquist's *Flora of the Pacific Northwest* (1973).

Field Code	**Native/ Exotic**	**Latin Name**	**Common Name**	**Classification**
ABGR	N	*Abies grandis*	Grand fir	T
ACGL	N	*Acer glabrum*	Douglas maple	T
ACMA	N	*Acer macrophyllum*	Big-leaf maple	T
ALCR	N	*Aluns crispa ssp. sinuata*	Sitka alder	T
ALRU	N	*Alnus rubra*	Red alder	T
BEOC	N	*Betula occidentalis*	River birch	T
COST	N	*Cornus stolonifera*	Red-osier dogwood	T
POTR	N	*Populus trichocarpa*	Black cottonwood	T
PSME	N	*Pseudotsuga menziesii*	Douglas fir	T
SAEX	N	*Salix exigua*	Coyote willow	T/S
SARI	N	*Salix rigida*		T/S
SASC	N	*Salix scouleriana*	Scouler's willow	T/S
SASI	N	*Salix sitchensis*	Sitka willow	T/S
TABR	N	*Taxus brevifolia*	Western yew	T
THPL	N	*Thuja plicata*	Western red cedar	T
TSHE	N	*Tsuga heterophylla*	Western hemlock	T
ACCI	N	*Acer circinatum*	Vine maple	S
BUDA	E	*Buddelja sp.*	Butterfly bush	S
COCO	N	*Corylus cornuta*	Beaked hazelnut	S
CYSC	E	*Cytisus scoparius*	Scotchbroom	S
GASH	N	*Gaultheria shallon*	Salal	S
LOIN	N	*Lonicera invulcrata*	Black twinberry	S
MANE	N	*Mahonia nervosa*	Oregon grape	S
OECE	N	*Oemleria cerasiformis*	Indian plum	S
PHCA	N	*Physocarpus capitatus*	Pacific ninebark	S
RHPU	N	*Rhamnus purshiana*	Cascara	S
RIBR	N	*Ribes bracteosum*	Stink currant	S
RIDI	N	*Ribes divaricatum*	Wild gooseberry	S
RILA	N	*Ribes lacustre*	Black gooseberry	S
RISA	N	*Ribes sanguineum*	Red-flowering currant	S
ROGY	N	*Rosa gymnocarpa*	Dwarf rose	S
RONU	N	*Rosa nutkana*	Nootka rose	S
RUDI	E	*Rubus discolor*	Himalayan blackberry	S
RULA	E	*Rubus laciniatus*	Evergreen blackberry	S
RUPA	N	*Rubus parviflorus*	Thimbleberry	S
RUSP	N	*Rubus spectabilis*	Salmonberry	S
RUUR	N	*Rubus ursinus*	Trailing raspberry	S
SARA	N	*Sambucus racemosa*	Red elderberry	S
SODU	E	*Solanum dulcamara*	European bittersweet	S
SPDO	N	*Spiraea douglasii*	Hardhack	S
SYAL	N	*Symphoricarpos albus*	Snowberry	S
VAPA	N	*Vaccinium parvifolium*	Red huckleberry	S
ACTR	N	*Achlys triphylla*	Vanilla leaf	H
ADBI	N	*Adenocaulon bicolor*	Pathfinder	H
ANMA	N	*Anaphalis margaritaceae*	Pearly everlasting	H
ASSU	N	*Aster subspicatus*	Douglas' aster	H
ASVI	N	*Asplenium viride*	Green spleenwort	H
ATFI	N	*Athyrium filix-femina*	Ladyfern	H
CIAL	N	*Circaea alpina*	Enchanter's nightshade	H
CIAR	E	*Cirsium arvense*	Canada thistle	H
CIVU	E	*Cirsium vulgare*	Bull thistle	H
CLPE	N	*Claytonia perfoliata*	Miner's lettuce	H
CLVI	E	*Clematis vitalba*	Clematis	H
DIAR	E	*Dianthus armeria*	Pink dianthus	H

DIFO	N	*Dicentra formosa*	Bleeding heart	H
DIPU	E	*Digitalis purpurea*	Foxglove	H
DREX	N	*Dryopteris expansa*	Spiny wood fern	H
EPCI	N	*Epilobium ciliatum*	Purple willowherb	H
EPLA	N	*Epilobium latifolium*	River beauty willowherb	H
EQAR	N	*Equisetum arvense*	Horsetail	H
EQHY	N	*Equisetum hyemale*	Scouring rush	H
ERPH	N	*Erigeron philadelphicus*	Philadelphia Fleabane	H
FRVE	N	*Fragaria vesca*	Strawberry	H
GATR	N	*Galium triflorum*	Bedstraw	H
GEMA	N	*Geum macrophyllum*	Geum	H
GERO	E	*Geranium robertianum*	Geranium	H
GLHE	E	*Glecoma hederaceae*	Creeping Charlie	H
HYPE	E	*Hypericium perforatum*	St. John's wort	H
HYRA	E	*Hypochaeris radicata*	Hairy cat's ear	H
LAMU	E	*Lactuca muralis*	Wall lettuce	H
LEVU	E	*Leucanthemum vulgare*	Oxeye daisy	H
MEAR	N	*Mentha arvens*	Field mint	H
MEAL	E	*Melilotus alba*	White sweet-clover	H
MOMA	N	*Moehringia macrophylla*	Big-leaved sandwort	H
PEPA	N	*Petasites palmatus*	Colt's foot	H
POCU	E	*Polygonum cuspidatum*	Japanese Knotweed	H
POGL	N	*Polypodium glycyrrhiza*	Licorice fern	H
POMU	N	*Polystichum munitum*	Swordfern	H
PRVU	N	*Prunella vulgaris*	Heal-all	H
RARE	E	*Ranunculus repens*	Creeping buttercup	H
RUAC	E	*Rumex acetosella*	Sheep sorrel	H
SADO	N	*Satureja douglasii*	Yerba buena	H
SIAN	N	*Silene antirrhina*	Sleepy catchfly	H
SIDI	E	*Silene dichotoma*	White silene	H
STCO	N	*Stachys cooleyae*	Hedgenettle	H
STCR	E	*Stellaria crispa*	Crisp sandwort	H
TABI	E	*Tanacetum bipinnatum* ssp. *huronense*	Dune Tansy	H
TOME	N	*Tolmiea menziesii*	Piggyback	H
TREU	N	*Trientalis europaea* var. *artica*	Broad-leaved starflower	H
TRLA	N	*Trientalis latifolia*	Western starflower	H
TRRE	E	*Trifolium repens*	White clover	H
URDI	N	*Urtica dioica*	Stinging nettle	H



Appendix B. Fit between annual peak flow data and log-Pearson Type III distribution used to determine flood frequency intervals for the five study reaches. Black triangles indicate the log-Pearson Type III distribution and grey triangles indicate all peak flows recorded by USGS for each reach. A tight fit between the two distributions validates the use of the log-Pearson Type III distribution in determining flood frequency intervals.



Appendix C. Fit between annual 7-day average low flow data and the log-Pearson Type III distribution, used to determine low flow frequency intervals for the three study segments (regulated (A), unregulated (B) and partially regulated (C)). Black triangles indicate the log-Pearson Type III distribution and grey triangles indicate the 7-day average low flow for each year recorded by USGS for each reach. A tight fit between the two distributions validates the use of the log-Pearson Type III distribution in determining low flow frequency intervals.

Appendix D. Scoring of the five individual criteria within the Recruitment Box Model.

Reach	**Year**	**1 Disturb.**	**2 Timing**	**3 Recession**	**4 Base Flow**	**5 Scour**	**Total Score**	**Predicted**	**Observed**
Regulated	1980	0	0	0	1	0	1	No	No
	1981	0.66	0	1	1	2	4.66	Yes	Yes
	1982	0.66	1	1	1	2	5.66	Yes	Yes
	1983	0	0	1	1	0	2	No	No
	1984	0.66	0	1	1	2	4.66	Yes	No
	1985	0.66	1	0	1	0	2.66	No	No
	1986	0	1	1	1	2	5	Yes	Yes
	1987	0	1	1	1	2	5	Yes	Yes
	1988	0	1	0	1	0	2	No	Yes
	1989	0	0	0	1	0	1	No	Yes
	1990	0.33	0	1	1	0	2.33	No	Yes
	1991	1	0	1	1	4	7	Yes	No
	1992	1	1	0	1	2	5	Yes	Yes
	1993	1	1	0	0	2	4	Yes	Yes
	1994	0	0	0	1	0	1	No	Yes
	1995	0	1	0	1	0	2	No	No
	1996	1	1	0	1	0	3	No	No
	1997	1	0	1	1	4	7	Yes	Yes
	1998	1	1	0	0	0	2	No	Yes
	1999	1	0	1	1	0	3	No	Yes
	2000	0.66	1	0	1	2	4.66	Yes	Yes
	2001	0.66	1	0	1	0	2.66	No	Yes
Unregulated	1980	0.66	1	1	1	0	3.66	No	No
	1981	0.66	1	1	1	0	3.66	No	No
	1982	1	1	1	1	0	4	Yes	No
	1983	1	0	1	1	0	3	No	No
	1984	1	1	1	1	2	6	Yes	No
	1985	1	1	1	1	0	4	Yes	Yes
	1986	0.66	1	1	1	0	3.66	No	No
	1987	0.66	1	1	1	2	5.66	Yes	Yes
	1988	0.33	1	1	1	0	3.33	No	No
	1989	0	1	1	1	0	3	No	No
	1990	0.66	1	1	1	0	3.66	No	No
	1991	1	0	1	1	2	5	Yes	Yes
	1992	1	1	1	1	0	4	Yes	Yes
	1993	1	1	1	1	2	6	Yes	Yes
	1994	1	1	1	1	0	4	Yes	Yes
	1995	0	1	1	1	0	3	No	Yes
	1996	1	1	1	1	0	4	Yes	Yes
	1997	1	0	1	1	2	5	Yes	No
	1998	1	1	1	1	0	4	Yes	No
	1999	1	1	1	1	0	4	Yes	Yes
	2000	0.33	1	1	1	2	5.33	Yes	Yes
	2001	0	1	1	1	0	3	No	Yes

Appendix D continued.

Reach	**Year**	**1 Disturb.**	**2 Timing**	**3 Recession**	**4 Base Flow**	**5 Scour**	**Total Score**	**Predicted**	**Observed**
Partially-Regulated	1980	1	0	0.5	1	0	2.50	No	No
	1981	1	1	1	1	0	4	Yes	No
	1982	1	1	0	1	0	3	No	No
	1983	1	0	0	1	0	2	No	No
	1984	0.66	1	0.5	1	2	5.16	Yes	No
	1985	0.66	1	1	1	0	3.66	No	No
	1986	0.33	1	0.5	1	0	2.83	No	No
	1987	0	1	0.5	0	2	3.50	No	No
	1988	0	1	1	1	0	3	No	No
	1989	0	1	1	1	0	3	No	No
	1990	0.66	0	0.5	1	0	2.16	No	Yes
	1991	1	0	0	1	2	4	Yes	Yes
	1992	1	1	0.5	1	4	7.5	Yes	Yes
	1993	1	1	0	1	2	5	Yes	Yes
	1994	1	1	1	1	0	4	Yes	Yes
	1995	0	1	1	1	0	3	No	No
	1996	1	0	1	1	0	3	No	No
	1997	1	0	0.5	1	4	6.50	Yes	Yes
	1998	1	1	1	1	0	4	Yes	Yes
	1999	1	1	0	1	0	3	No	Yes
	2000	0.66	1	1	1	2	5.66	Yes	Yes
	2001	0.66	1	0	1	0	2.66	No	No