King County

King County Department of Natural Resources and Parks
Water and Land Resources Division
Normative Flow Project
Technical Memorandum
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RE: Literature Review of Indicators Potentially Supporting a Method to Relate Human Actions, Instream Flow and Biological Conditions in Puget Sound Lowland Rivers and Streams

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Please see the attached report summarizing the work of the technical leads in reviewing and synthesizing literature relevant to the choice of indicators for the Normative Flow Project.

Literature Review: Effects of Flow Alteration on Aquatic Ecosystems

Normative Flow Project

King County

Department of Natural Resources and Parks
Water and Land Resources Division

Prepared by
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PURPOSE/OBJECTIVE

The primary objective of this literature review is to support the development of a method that can be used to evaluate the effects of specific flow alterations on aquatic ecosystems in King County for the Normative Flow Project (NFP). A particular focus of this project is to evaluate effects of flow alteration that are relevant to the conservation of a diverse suite of native species, including salmonids, in King County rivers and streams.

The review addressed the following general questions:

- What is currently known regarding relationships between flow regimes and ecological responses in aquatic systems – especially in the PNW?
- Are there relationships that have been empirically documented or quantified, especially under a range of flow conditions?
- Which responses to flow alteration have been most frequently documented in the literature?
- Which types of flow alteration (magnitude, frequency, duration, timing, rate of change) are most often linked with biological or physical responses?
- Are there useful indicators of biological or geomorphic response to flow alteration that could be used to describe or evaluate effects of flow alteration on King County streams and rivers?

METHODS

The primary focus of this review was to evaluate the current literature on biological and physical effects of flow alteration on river and stream ecosystems, and summarize what is known about relationships between specific flow changes and biological or physical responses. We concentrated on reviewing references published since the Poff et al. (1997) review. That review

included a thorough summary of papers published prior to 1997 on responses of aquatic ecosystems to flow; some additional pre-1997 references are included this review to provide a complete summary of the known effects of flow on river systems.

In the Normative Flow Project literature review we selected papers that explicitly tested relationships between flow alterations and responses of river and stream systems, or papers that established significant correlations between patterns of flow variation and river condition. Although the Normative Flow Project has a regional focus on the lowland rivers and streams of western Washington, the literature review surveyed papers from all over the world. Much of the current research on the effects of flow alteration is being conducted in Australia, South Africa and Europe. Therefore, even though these river systems differ in significant ways from King County streams and rivers, including this literature in the review is important for documenting general ecological responses of rivers to flow alteration.

Approximately 500 papers published since 1997 were reviewed. A smaller set of about 200 references that include specific tests of predictions about flow alterations or establish significant correlations between flows and river condition are summarized in the annotated bibliography and attached table summarizing responses to flow alteration.

Because research on the ecological effects of flow alteration continues to expand rapidly, King County should update this literature review with the results of on-going research. This review should be maintained as a current summary of existing literature on the ecological effects of flow alteration.

RESULTS

Results of the literature review are summarized primarily in the attached table "Ecological Effects of Flow Alteration" and in the annotated EndNote Bibliography, "Normative Flow Project – Ecological Effects of Flow Bibliography". The Ecological Effects table is organized by type of category of response (biogeochemical, geomorphic, biological – individual/population/ community) and type of hydrologic alteration (magnitude, frequency, duration, timing, rate of change).

In addition, the major classes of biological responses to flow alteration from the literature are summarized in Tables 1 & 2. Major classes of response to flow alteration and the types of responses are the basis of many of the biological and geomorphic indicators of hydrologic alteration developed as part of the Normative Flow Project and described in the technical memorandum on that topic.

Table 1. Effects of Flow Alteration on Riparian Vegetation

Vegetation Attribute Affected by Flow	Flow Alteration	References
Growth rates and biomass:		
Reduced growth rates	Prolonged low flows	Stromberg et al. 1992; Reily and Johnson 1982;
Reduced biomass	Elimination/reduction of peak flows Reduced magnitude of flows Reduced magnitude of growing season flows	Perkins et al. 1984; Kondolf and Curry 1986; Rood et al. 1995
Increased growth rates Increased biomass	Magnitude of average flows; magnitude of low flows Volume of stream flow during current year	Stromberg and Patten 1990
Change in timing of period of maximum growth	Change in timing of floods from spring to summer/fall; Timing of high flows changes from spring to summer	Robertson et al. 2001Stromberg and Patten 1990
Change in timing of leaf drop	Change in timing of floods from spring to summer/fall;	Robertson et al. 2001
Reduced survival riparian trees and shrubs	reduction in annual mean discharge resulting in lowered water tables in floodplain	Segelquist et al. 1993
Morphological/physiological responses:		
Reduced leaf area Reduced water potential/increased water deficits	Reduction flow volumes during growing season; Depth to groundwater as correlated with annual discharge; magnitude and duration of peak flows	Stromberg 1993
Differential water uptake by roots (deep vs. surface water)	Reduced stream flows	Smith et al. 1991
Dispersal:		
Dispersal reduced and composition of seed bank (reduced abundance of short-floating species); recruitment processes	fragmentation by dams; impounded sections (lentic vs. lotic habitat); reduction in flood flows and reduction in mean annual flows;	Andersson et al. 2000

Table 1 Continued.

Vegetation Attribute Affected by Flow	Flow Alteration	References
Dispersal reduced and composition of seed bank (reduced abundance of short-floating species); recruitment processes	longitudinal connectivity lost through dams and flow diversions	Andersson et al. 2000; Jansson et al. 2000; Shafroth et al. 1998
washout of plants; failure of seedling establishment	rate of change; more rapid rates of rise and fall during water level fluctuations associated with dam operations (or increased flashiness of system?)	Grelsson 1986; Rood et al. 1995; Rood et al. 1999
Recruitment of riparian trees and shrubs:		
peak discharges linked to successful cottonwood recruitment	reduced magnitude of peak flows; peak flows > 1850 m3/s were associated with successful cottonwood establishment & were assumed to be the minimum flows necessary for cottonwood recruitment	Bovee and Scott 2002
reduced regeneration and recruitment of plants requiring periodic floodplain disturbance to regenerate	stabilized flow regimes	Fenner et al. 1985; Shankman and Drake 1990; Johnson 1994; Rood et al. 1995; Scott et al. 1997; Cordes et al. 1997
washout of plants; failure of seedling establishment	rate of change; more rapid rates of rise and fall during water level fluctuations associated with dam operations (or increased flashiness of system?)	Grelsson 1986; Rood et al. 1995; Rood et al. 1999
Change in species composition/community attributes:		
Reduced species richness downstream of dams and/or regulated reaches with reduced flows	rivers fragmented by dams; loss of longitudinal connectivity; reduced flows and lowered velocities	Andersson et al. 2000
plant species diversity; reduction in diversity of vegetation structural types from 4 to 1 due to elimination of regeneration sites/conditions for riparian cottonwood and willow	elimination of floods above 2500 m^3 sec^{-1};reduction in mean daily flows (by 80%)	Johnson 1993
loss of species with high regeneration and/or colonizing ability in areas that are infrequently flooded (disturbed)	reduced frequency of flooding	Barrat-Segertain et al. 1999

Table 1 Continued.

Vegetation Attribute Affected by Flow	Flow Alteration	References
replacement of emergent grasses with trees; change in physiognomy (structure; grassland to forest) as well as life history traits (inundation/summer drought tolerant to phreatophyte)	reduction in frequency and duration of floodplain inundation (from every 3 out of 4 years to less than 2 out of 4; from 9+ months to less than 4); change in timing of flood flows (from large winter floods to small summer floods); reduced area of floodplain inundated (from 75% to 10%)	Bren 1992; Bren 1988
increased extent and abundance of exotic plant species in riparian vegetation	reduced frequency of flooding; changed timing of flooding; increased dry season base flows; decreased dry season base flows	Busch and Smith 1995; Friedman et al. 1998; Bren 1988
altered species composition in riparian plant communities	duration; prolonged inundation; changed timing of seasonal inundation and low flows	Connor et al. 1981; Bren 1992; Crivelli et al. 1995; Toner and Keddy 1997; Friedman and Auble 1999; Galat and Lipkin 2000
expansion of forest/woody vegetation into river corridor (I.e., below former water line)	elimination/reduction of annual flooding	Gill, 1973; Toner and Keddy 1997; Grelsson and Nilsson 1980; Johnson 1994 - cited in Nilsson and Svedmark 2002
replacement of lotic stream habitat with more lentic habitat dominated by aquatic macrophytes (Typha) where aquatic macrophytes formerly did not exist	dry season flows changed from 4% of annual flow to 32%; ephemeral reaches become perennial	Goes 2002
invasion by Russian olive/tamarix; conversion from herbaceous/emergent to woody wetland vegetation	change in timing of high flows; loss of seasonal flow peaks	Horton 1977; Friedman et al. 1998; Toner and Keddy 1997; Springer et al. 1999; Hill et al. 1998
number of plant species reduced (decline in biodiversity)	reduced current velocities and increased amount of open water habitat in regulated rivers below dams	Jansson et al. 2000 - cited in Nilsson and Svedmark 2002
proportion of short-floating species represented in riparian vegetation was reduced	reduced current velocities and increased amount of open water habitat in regulated rivers below dams	Jansson et al. 2000 - cited in Nilsson and Svedmark 2002
reduced area and diversity of wetland vegetation	reduced frequency, duration and area of inundation of floodplain wetlands/off-channel habitat	Kingsford 2000

Table 1 Continued.

Vegetation Attribute Affected by Flow	Flow Alteration	References
reduced growth and survival of native aquatic macrophytes; increased invasion of non-native species	elimination of seasonal wet-dry cycles; increased stability of water levels	Kingsford 2000; Mitchell and Gopal 1991
replacement of native cottonwood forests with Russian olive-dominated forests along northern Great Plains rivers	reductions in magnitude of peak flows	Lesica and Miles 1999
% cover exotic plant species correlated with duration of flooding and number of times per year that riparian zone was inundated	increased disturbance intensity and frequency as reflected in flood frequency (number events/year) and duration (days/year) related to increased cover of exotic species	Pettit et al. 2001
% cover shrubs negatively correlated with number of events per year that inundate riparian zone	increased disturbance frequency (number of events/year) correlated with decrease in shrub cover	Pettit et al. 2001
% cover of annual herbs positively correlated with duration of riparian zone inundation	as # days/year riparian zone is inundated increases, % cover of shrubs decreases (can't tolerate disturbance)	Pettit et al. 2001
change in species composition, reduced species diversity	increased variation in magnitude and frequency of flows	Petts 1984; Rorslett and Johansen 1996 - cited in Nilsson and Svedmark 2002
biomass of aquatic macrophytes; spring flooding (natural flow regime) was positively related to biomass; summer flooding was negatively related to biomass	change in timing of annual peak flows	Robertson et al. 2001
decline in forested/woody riparian vegetation	elimination/reduction of annual flooding	Rood and Heinze-Milne 1989; Pettit and Froend 2000 - cited in Nilsson and Svedmark 2002
reduced plant diversity	lateral disconnection via reduced flooding, incision or levees	Sparks et al. 1990; Theiling 1995; Ward and Stanford 1995; Brunke and Gonser 1997; Ward et al. 1999
floodplain plant community composition	frequency of floodplain inundating flows	Sparks et al. 1998

Table 1 Continued.

Vegetation Attribute Affected by Flow	Flow Alteration	References
replacement of herbaceous/emergent vegetation with woody vegetation	reduction in frequency and duration of annual floods (frequency and duration of inundation of floodplain) leads to an invasion of formerly herbaceous communities by woody vegetation) - best hydrological predictors were last day of the first flood of the season and the first day of the second flood	Toner and Keddy 1997
increased abundance/extent of non-native plants	stabilized flow regimes	Ward and Stanford 1979; Busch and Smith 1995; Stanford et al. 1996
reduced plant diversity; site and landscape scales	elimination peak flows; loss of channel forming/floodplain inundating flows	Ward et al. 1999; Marston et al. 1995; Hill et al. 1998; Galat et al. 1998; Schiemer et al. 1998

Table 2. Effects of Flow Alteration on Fish and Aquatic Invertebrates

Flow Affect on Fish or Invertebrates	Type of Flow Alteration	References
Growth rates and biomass:		
reduced salmon growth rates in estuaries and off-channel habitats	Reduced frequency and/or magnitude of overbank/floodplain inundating flows; timing of overbank flows; loss of connectivity between river and floodplain	Bottom et al. 2001
Reduced overwinter survival of juvenile salmonids	reduced frequency and/or magnitude of overbank flows; loss of connectivity between river and floodplain	Peterson and Reid 1984
Reduced growth rate of juvenile salmonids during years of high spring floods	Increased magnitude of spring peak flows	Jensen and Johnsen 1999
lowered productivity of estuarine fish and invertebrates; reduced biomass and growth rates of fish in estuary	flow regulation by dams; altered seasonal inflows to estuary; higher inflows of freshwater to estuary in late summer and fall	Finch 1998
Reduction in standing crop (biomass) of benthic macroinvertebrates	Rapidly fluctuating flows below dams; increased number of reversals (daily); increased variability (daily) in flows	Layzer et al. 1989; Petts 1984 (numerous citations)
reduced biomass and abundance of aquatic insects	elimination of flooding resulting in elimination of lateral channel meandering and off-channel habitat	Mestl and Hesse 1993 (cited in Pringle et al. 2000)
Survival:		
reduced survivorship of larval atyid shrimp following early summer spates	Changed timing (occurrence of a-seasonal) of spates	Hancock and Bunn 1997 (cited in Bunn and Arthington 2002)
reduced survival of salmonid smolts;	anomalously high annual discharges (defined as >20% increased compared to previous 3 year average)	Beamish et al. 1994
reduced survival of alevin and emerging fry	increased magnitude of high spring flows	Jensen and Johnsen 1999
decreased egg survival	magnitude of peak discharges	Sear 1993

Table 2. Continued

Flow Affect on Fish or Invertebrates	Type of Flow Alteration	References
negative effects of high discharges on egg and alevin survival via movement of bedload, scouring redds	high discharges	DeVries 1997
reduced egg survival; with floods of <10 yr recurrence, probability of egg clutch scour was 5%; with 1 in 100 yr floods, probability was 20%	frequent floods (<10 yr recurrence)	Lapointe et al. 2000
Physical displacement:		
displacement of young fish	increased velocity at higher discharge	Elwood and Waters 1969; Heggenes and Traaen 1988
increased drift of periphyton-associated macroinvertebrates with increased flow rates in New Zealand rivers	magnitude of flow rates; rate of change of flow rates	Irvine and Henriques 1984
Habitat availability and accessibility:		
density of juvenile/larval fish in river reduced when connectivity is lost	timing/magnitude/duration of floodplain inundating flows correlated with juvenile abundance	Shaeffer and Nickum 1986 b, Amoros and Roux 1988, Copp 1989
Recruitment:		
loss of cues for spawning and/or migration	changed timing of rising flows	Lowe-McConnell 1985; Nesler et al. 1988; King et al. 1998
Reduced spawning & recruitment success of riverine fish	changed timing of spates; a-seasonal spates during low flow periods	Milton and Arthington 1983; 1984; 1985; Humphries and Lake 2000
Delayed spawning in fish	modified temperatures below dams; modified temperatures when groundwater inputs have been changed	Zhong and Power 1996

Table 2. Continued

Flow Affect on Fish or Invertebrates	Type of Flow Alteration	References
change in reproductive timing; reduced reproductive success of prairie fishes; reduced egg survival	reduction in flood flows and flow stabilization	Cross and Moss 1987 (cited in Pringle et al. 2000) & Echelle et al. 1995
inter-annual variability in reproductive success (juvenile production) related to flow variability; recruitment success differs among species each year resulting in more diverse fish assemblages	increase in flow fluctuations due to hydropeaking (esp. in summer); decrease in median spring and summer flows in regulated reaches compared to pre-dam and unregulated reaches	Freeman et al. 2001; Sparks 1995; Walker and Thoms 1993
Community attributes/species composition:		
abundance of native fish declined with flow alterations abundance of non-native fish species increased with flow alterations	lower low flows, greater numbers of reversals, lower maximum stage levels, and shorter spring flood periods associated with greater abundance of non-native species and reduced abundance of native species	Koel and Sparks 2002
Change in fish community composition (loss of shallow-water specialists)	Increased flow fluctuations; greatly increased magnitude of daily peaks	Bowen et al. 1998
reduced abundance of salmonid species	increase in frequency of peak flows; 10 yr floods are now 1-4 yr floods	Moscrip and Montgomery 1997
increased abundance/dominance of exotic fish species	conversion of lotic to lentic habitats (impoundments, reductions in mean annual or base flows)	Arthington and Bluhdorn 1994; Davies and Day 1998 (cited in Bunn and Arthington 2002)
percentage of non-native fish increased with lower spring flows in the previous year	mean flows during spring (April/May)	Brown and Ford 2002
change in fish species composition, range expansion of salt tolerant species	reduce discharge in streams due to water withdrawals; intrusion of salt water into river mouth	Contreras and Lozano 1994
Reduced species richness in fish	reduction of flow variability; increase in stability and magnitude of baseflows	Converse et al. 1998 (cited in Bunn and Arthington 2002)

Table 2. Continued

Flow Affect on Fish or Invertebrates	Type of Flow Alteration	References
changes in relative abundance of fish species (YOY); changes in relative abundance of spring vs. summer spawning species; spring spawning species were less abundant in flow-regulated reach; regulated river was dominated by fish that can extend spawning to summer months	increase in flow fluctuations due to hydropeaking (esp. in summer); decrease in median spring and summer flows in regulated reaches compared to pre-dam and unregulated reaches	Freeman et al. 2001
increased invasion of non-native fish species	elimination/reduction of flow variability; increased seasonal stability (I.e., decreased variability between seasons)	Faragher and Harris 1994; Walker et al. 1995; Gehrke et al. 1999 (cited in Bunn and Arthington 2002)
changes in relative availability and/or persistence of different habitat types (shallow-slow; shallow-fast; deep-fast) among seasons between regulated and unregulated reaches	increase in flow fluctuations due to hydropeaking (esp. in summer); decrease in median spring and summer flows in regulated reaches compared to pre-dam and unregulated reaches	Freeman et al. 2001
negative correlation between YOY abundances and availability of shallow-fast habitats and with summer peak flows - I.e., stable low flows are necessary for survival of some fish species native to river	increase in flow fluctuations due to hydropeaking (esp. in summer); decrease in median spring and summer flows in regulated reaches compared to pre-dam and unregulated reaches	Freeman et al. 2001; Sparks 1995; Walker and Thoms 1993
native fish species populations showed negative response to flow regulation	flow regulation by dams and irrigation diversion; most frequently reduced seasonal flooding and increased baseflows during drought seasons	Gehrke and Harris 2001
change in fish species composition; loss of salmon species, retention of cutthroat	increase in frequency of peak flows; 10 yr floods are now 1-4 yr floods	Moscrip and Montgomery 1997
reduced areas for spawning and/or recruitment success for lowland river fish	reduced frequency, duration and area of inundation of floodplain wetlands/off-channel habitat	Welcomme 1979, Geddes and Puckridge 1989, Cadwallader and Lawrence 1990
shift in recruitment from floodplain spawners to in-channel spawners	rapid fall rate; rapid pulse recession	Welcomme 1989

Table 2. Continued

Flow Affect on Fish or Invertebrates	Type of Flow Alteration	References
zooplankton community composition; abundance of rotifers and crustaceans in off-channel habitats	connectivity of floodplain and river; 'water age' a measure of 'lotic' character of water - river water is age 0; the lower the age the greater the connectivity with river water	Baranyi et al. 2002
reduction in species richness and abundance (freshwater shrimp)	reduced flows due to water withdrawals	Benstead et al. 1999
diversity of carabid beetles was greater along rivers with unregulated flow regimes compared to regulated rivers; mostly because specialist species adapted to particular flooding regimes were absent from regulated rivers	reduction/elimination of spring floods; reduced frequency and duration of overbank flows and floodplain inundation	Bonn et al. 2002
species extinction? (grazers)	fluctuating flows (daily alternation of desiccation and inundation of algal biofilms)	Burns and Walker 2000
benthic species richness, biomass, density were negatively and positively related to flood frequency; response of periphyton and invertebrates differed	FRE3 (flood frequency - flood is flows higher than 3X the median flow) best overall flow variable; flood frequency variables in general were correlated with biota	Clausen and Biggs 1997
change in functional groups - reduction in shredders and increase in filter feeders	reduction in flow variability - constant flow regime	Cortes et al. 2002
change in location of benthic and epibenthic invertebrates within estuary related to steepening of river delta slopes	reduction in flow - diversion of 40% of annual average runoff from basin	Jay and Simenstad 1996
Relative densities of invertebrates in wetlands changed in response to different flooding regimes; ostracods adapted to colonize ephemeral wetlands were less abundant in permanently flooded systems	changed timing of flooding of riverine wetlands; changed duration of flooding - permanently flooded vs. ephemeral wetlands	Nielsen et al. 2002