United States Department of the Interior

FISH AND WILDLIFE SERVICE

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In Reply Refer To:
AFWO

Technical Memorandum

TO: Dave Hillemeier, Yurok Tribal Fisheries, and
Craig Tucker, Karuk Department of Natural Resources

FROM: Conor Shea, Nicholas J. Hetrick, and Nicholas A. Som, Arcata Fish and Wildlife Office

SUBJECT: Response to Request for Technical Assistance – Sediment Mobilization and Flow History in Klamath River below Iron Gate Dam

DATE: September 29, 2016

Purpose. The Arcata Fish and Wildlife Office (AFWO) Fisheries Program is working with its scientific co-investigators to develop a series of four technical memorandums that summarize recent findings of studies that contribute to our current understanding of *Ceratanova shasta* (syn *Ceratomyxa shasta)* infections in the Klamath River, in response to requests for technical assistance from the Yurok and Karuk tribes. Each of the topics addressed in the four technical memorandums: 1) sediment mobilization review and streamflow history for the Klamath River below Iron Gate Dam, 2) polychaete distribution and infections, 3) actinospore and myxospore concentrations, and 4) prevalence of *C. shasta* infections in juvenile and adult salmonids, are identified in a conceptual model diagram (Figure 1) taken from Foott et al. (2011) and as discussed with the requesting tribes. The intent of the technical memorandums is to provide managers with a contemporary understanding of the state of the science with regard to the *C. shasta* in the Klamath River, and to provide a scientific basis to inform and support resource management decisions. The focus of this technical memorandum is to summarize the state of knowledge regarding environmental flow releases from the Iron Gate Dam to achieve specific objectives for channel form and ecological function. Other memorandums in this series will address how achieving these objectives will potentially influence various aspects of the *C. shasta* life cycle and population.

In this technical memorandum, we first summarize the state of knowledge regarding environmental flows to achieve specific objectives for channel form and ecological function. Then, the memorandum reviews estimates of flows necessary for achieving several channel substrate movement states in the Klamath River below Iron Gate Dam that were developed by three different research teams. The final section of the memorandum examines the frequency, magnitude, and duration of sediment mobilization flows for the Klamath River below Iron Gate Dam that have occurred since dam construction.

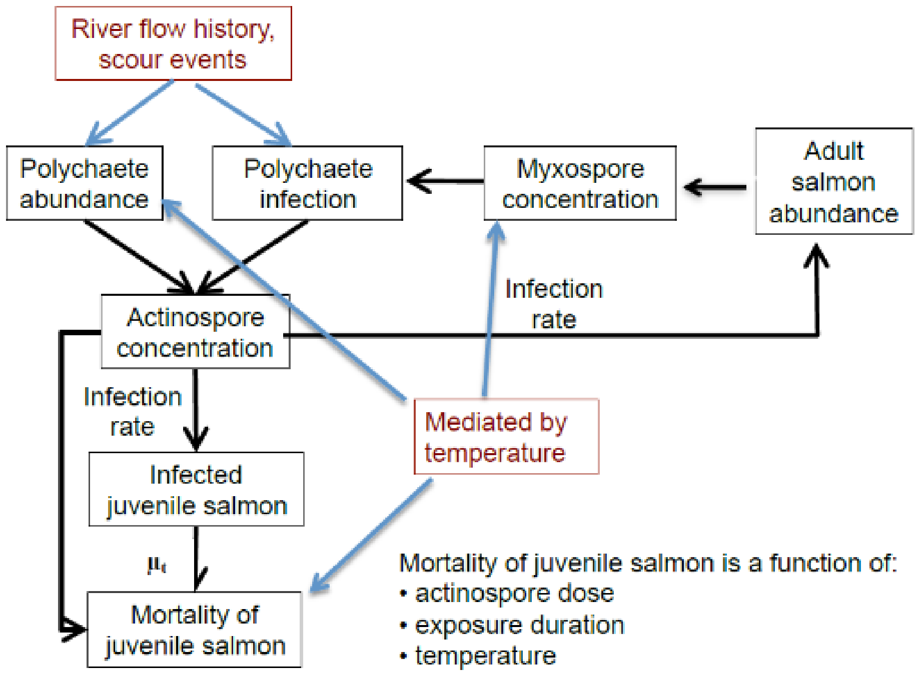

Figure 1. Conceptual model for variables that influence infection and mortality of juvenile Chinook Salmon, with μ_t being the mortality rate of infected juvenile salmon, estimated from weekly actinospore concentrations in water samples. (taken from Foot et al. 2011).

Environmental Flows. The physical and ecological responses of a river to construction of a dam or diversion of flow have been recognized for many years (Rathburn et al. 2009). A river's planform and cross section are formed in response to the flow that the river receives, the character and rate of sediment supplied to and transported by the river, and the characteristics of the vegetation, sediment, and substrate comprising the channel through which the river flows (Leopold, 1994). Similarly, a river's ecosystem is regulated and maintained by the temporal distribution, duration, and magnitude of floods and low flows (Karr 1991). The construction of dams and/or the creation of water diversions alter the natural hydrologic and geomorphic processes that maintain river form and habitat for aquatic and riparian species. Physical responses to dam construction or diversions can include downstream channel erosion and coarsening of bed substrate due to reduced sediment supplies, deposition of sediment on the bed due to reduced transport capacities, decreases in channel width and depth, and floodplain disconnection due to reduced magnitude and frequency of high flows (Kondolf and Wilcock, 1996, Williams and Wolman, 1984). Alterations to the flow regime likewise change the timing and movement of sediment, biological materials, and energy within rivers and between rivers and their floodplains, which disrupts the life cycles of riparian and aquatic species adapted to an undisturbed regime (Poff et al. 1997).

Definition. Environmental flows are developed by river managers to mitigate the detrimental impacts of dams and water diversions on river form and ecological functions. The term *environmental flow* as used in this memorandum is defined as the water regime in a river implemented to maintain geomorphic form, riparian and aquatic ecosystems, and their related benefits where flows are regulated. Environmental flows mimic components of natural flow variability including the magnitude, frequency, duration, timing, and sequencing of both high and low flow events (Arthington et al. 2006). Environmental flow regimes can include diverse components designed to meet specific physical objectives such as maintaining aquatic habitat; removal of accumulated fine sediments; maintaining sediment balance, remobilization of gravels and formation of bars, scouring of vegetation, overtopping riverbanks with flow and sediment to augment floodplain development (Whiting 2002).

Environmental flow regimes designed to induce geomorphic changes can be broadly divided into two categories: (1) *sediment maintenance flows* (also commonly called *flushing flows*) that are made with the objective of removing sediment from a channel or otherwise modifying substrate composition; and (2) *channel maintenance flows* which are flow regimes intended to maintain channel form and floodplains (Kondolf and Wilcock 1996).

Identifying Physical Outcomes. River restoration activities often have poorly defined goals and fail to specify desired project outcomes (Bernhardt et al. 2005). Similarly, environmental flow releases are often made without a clear statement of desired physical outcomes and with insufficient consideration of the physical changes that a particular environmental flow regime will create (Kondolf and Wilcock 1996). To be effective, environmental flow objectives need to be specified in terms of desired physical responses. Table 1 presents a list of common geomorphic goals with corresponding physical objectives and required environmental flow parameters.

Development of flow releases from Iron Gate Dam that are intended to adversely impact the *C. shasta* life cycle by targeting the disruption of the obligate invertebrate host as suggested by Alexander et al. (2016) should identify specific physical objectives. The specification should identify the desired form of bed modifications (e.g., sand mobilization or gravel mobilization) and the extent of the mobilization (e.g., from riffles, from channel margins, from pools, etc.). The frequency and seasonal timing of environmental flows should also be specified. Seasonal timing should be based on biological objectives and constraints. Seasonal timing might also be based on physical objectives such as sequencing flows to occur simultaneously or following unregulated tributary peak flows.

In developing environmental flow regimes, it is important to recognize conflicts in objectives and constraints on flow releases. Wilcock et al. (1996b) describes the conflict in developing flushing flow recommendations for the Trinity River below the Lewiston Dam. Optimizing the removal of fine sediment from channel would result in loss of supply limited gravel. Flushing flows were set to balance competing objectives. Constraints on flow releases may involve limits in the water available for flow due to drought or competing uses, concerns over lost power generation, and undesirable flooding or channel adjustments for downstream landowners.

Table 1. Flushing flow and channel maintenance flow goals, objectives, and requirements (adapted from Kondolf and Wilcock 1996).

Flow Regime	***Management Goal***	***Specific Objective***	***Flow Requirement***
Flushing Flow	Restore riffle habitat	Remove surficial fine sediment[1] from riffles	Generate shear stress (τ_0) sufficient to transport sand particles on riffles
		Remove interstitial fine sediment	Generate shear stress (τ_0) sufficient to entrain surface gravels
	Improve spawning gravels	Increase gravel porosity (i.e. loosen gravel)	Generate shear stress (τ_0) sufficient to entrain surface gravels
	Improve pool habitat	Scour accumulated fine sediments	Transport net sand out of pools
Channel Maintenance Flow	Maintain/Restore Channel Width, Depth and Topographic Diversity	Mobilize surface gravel layer throughout cross section	New projects [2]: Release flow equivalent to the pre-project effective (channel forming) discharge
			Old projects: Generate shear stress (τ_0) sufficient to entrain on bar surfaces
	Reduce riparian encroachment	Uproot seedlings on bar surfaces	Generate shear stress (τ_0) sufficient to entrain gravel on bar surfaces
		Remove established vegetation	May require large flow on order of 10-20 year return period
	Create/build floodplain habitat	Create vertical accretion on floodplains	Produce muddy over-bank flow (requires source of suspended sediment)
	Create diverse multiage riparian habitat	Induce channel migration and create diverse geomorphic surfaces	Flow sufficient to erode banks, deposit point bars, and create overbank deposits

Notes:
(1) Fine sediment refers to sediment where the particle diameter along the intermediate axis is less than or equal to 2 mm. Coarse sediment refers to sediment where the particle diameter along the intermediate axis is greater than 2 mm.
(2) The term new projects refers to new dams or diversions where the river retains its original form. The term old projects refers to locations where the river has undergone long-term adjustments in form in response to a dam or diversion.

Analysis Methods. Kondolf and Wilcock (1996) characterize three methods for estimating flushing flows and channel maintenance flows:

- Self-adjusted channel methods employ the assumption that the flushing flows should mimic the pre-project effective discharge (e.g., Andrews and Nankervis, 1995). Use of self-adjusted channel methods requires the assumption that the river was previously in an equilibrium condition.

- Sediment entrainment methods employ sediment transport relationships to estimate the thresholds for sand and gravel entrainment. Local observations of stream sediment and hydraulic properties are used to develop estimates. Use of these methods does not require the assumption that the river is in an equilibrium condition.

- Direct calibration methods require extensive monitoring during pilot environmental flow releases. Observations are made of flow velocity, total discharge, bed movement and sediment transport for flow events that mobilize sediment. Direct calibration methods allow for estimates of volume of sand and gravel that are mobilized (Wilcock et al. 1996a), which are critical to developing a balanced sediment regime (Wohl et al. 2015; Schmidt and Wilcock 2008).

The Role of Adaptive Management. Environmental flows should be implemented within an adaptive management framework (e.g., see Williams and Brown 2012). Projecting the responses of environmental systems to management actions often involves uncertainties. Developing environmental flows targeted at disrupting M. speciosa will involve uncertainties in the biological response, sediment transport relationships, and meteorological and channel conditions prior to releases. Development of environmental flows should be seen as an iterative process of developing flow regimes, implementing and monitoring the environmental flow, followed by assessment of sediment transport, biological response, and sediment storage on a reach by reach basis in downstream areas.

Klamath River Sediment Entrainment Analyses. There are three recent studies that developed estimates of sediment transport thresholds in the Klamath River below Iron Gate Dam (Ayres Associates, 1999; Holmquist-Johnson and Milhous, 2010; and Reclamation, 2011). These studies employ uncalibrated sediment transport relationships to develop estimates of discharge required to initiate various stages of sediment mobilization. Local observations of stream sediment and hydraulic properties are used to develop the estimates.

Although terminology and methods differs slightly between the three studies, each of the studies characterizes the channel substrate as consisting of several sediment layers:

- a mobile surface layer of fine sediment (sand, silt, and clay sized particles having median grain diameters less than 2 mm);
- an armor layer consisting of sorted coarse sediment (gravel, cobbles and boulders having median grain diameters greater than 2 mm) 1-2 grain diameters in thickness; and
- an underlying substrate layer, less coarse than the armor layer, and containing a mixture of coarse and fine sediment.

The actual composition of the channel substrate material varies with location relative to dams and tributaries. There are areas directly below Iron Gate Dam, which have reduced coarse grain material input due to sediment trapping behind the dam, where the armor layer has been winnowed out and a pavement layer has developed that consists of large coarse sediment (cobbles and boulders) that are several grain diameters in thickness. In other areas where fine sediment supplies are high and entrainment flows low, the armor layer has infilled with fine sediment.

The three studies develop estimates of the discharge required to achieve several sediment mobilization states. Again, terminology differs slightly between the three studies. In this memorandum, we employ the terms listed in Table 2 to describe differing degrees of sediment mobilization. The discharges ranges established by the three studies for the sediment mobilization states should be understood to be approximate values and that transitions between sediment mobilization states occur gradually, not with sudden jumps when a threshold value is exceeded.

Table 2. Sediment mobilization state definitions.

Immobile Bed	No movement of surface sediment, armor layer or substrate. Deposition of suspended sediment absorbed into voids (until full).
Stable Bed	No movement of surface sediment, armor layer or substrate. Suspended sediment in water column remains in transport.
Surface Flushing	Movement of surface fine layers on 20-30% of bed.
Depth Flushing	Removal of in-filled fine sediment from armor layer.
Armor Disturbance	Movement of individual armor layer particles.
Armor Layer Movement	Reworking of armor and substrate layers

Ayres Associates (1999). Ayres Associates prepared a geomorphic and sediment evaluation of the Klamath River from Iron Gate Dam to the ocean for the U.S. Fish and Wildlife Service (Ayres Associates, 1999). Much of the study report covers the geomorphic assessment of the river and the report provides substantive descriptions of the geomorphic controls shaping the river.

Ayres Associates (1999) conducted their field work for the report in 1997. In the period from fall 1992 to spring 1997, there were six flow events in which the daily-mean flows at Iron Gate Dam exceeded 6,030 cubic feet per second (cfs), which Reclamation (2011) estimates is the two-year return period discharge for the Klamath River below Iron Gate Dam. Daily-mean flow reached 18,500 cfs on January 1, 1997, the second highest flow since dam closure. Ayres Associates (1999) observed that neither aggradation nor channel degradation (downcutting) was apparent in the reach of the Klamath River between Iron Gate Dam and the Shasta River. They also observed that pools did not appear to be infilling with sediment and that there was minimal infilling of coarse bed substrate with fine sediment.

Ayres Associates (1999) surveyed a series of cross sections at each of six study sites. Three of the study sites were located between Iron Gate Dam and Seiad Creek. Ayres Associates used the cross sections and water surface elevation measurements to develop and calibrate 1-D hydraulic models of the study sites using Version 2.0 of the U.S. Army Corps of Engineers HEC-RAS computer program.

Ayres Associates (1999) conducted an incipient motion analysis using the hydraulic analysis to determine critical shear stress and critical discharge necessary to initiate movement of sediment from riffles and pools. The incipient motion analysis used the Shields' relationship:

$$\tau_c=\theta(\gamma_s-\gamma)D_c \quad (1)$$

where:

τ_c	is the critical shear stress required to initiate sediment transport
θ	is the Shield's parameter
D_c	is the representative sediment size
γ	is the specific weight of water
γ_s	is the specific weight of sediment

Ayres Associates (1999) set the value of D_c to the value of the median grain size (D_{50}) found on pools and riffles during site investigations. Ayres Associates (1999) set the value of the Shield's parameter to 0.047 for fine sediment and 0.035 for coarse sediment.

Ayres Associates (1999) used the U.S. Army Corp of Engineers HEC-RAS model to determine the critical discharge (Q_c) that would generate the critical shear stress calculated in equation (1) to mobilize sediment from pools and from riffles at the six study sites. Boundary shear stress was calculated using:

$$\tau_o = \frac{\rho V^2}{\left[5.75 \log\left[12.27\frac{y_o}{k_s}\right]\right]} \quad (2)$$

where:

τ_o	is the cross section average hydraulic shear stress on the bed
ρ	is water density
V	is the cross section average flow velocity
y_o	is the cross section average flow depth
k_s	is the equivalent roughness height of the substrate

Ayres Associates (1999) set the equivalent roughness height to $3.5*D_{84}$ for coarse sediment (surface $D_{50} > 2$ mm) and to D_{84} for fine sediment (surface $D_{50} < 2$ mm). They identified the critical discharge (Q_c) required to initiate sediment motion as the mean discharge where the boundary shear stress equaled the critical shear stress ($\tau_0 = \tau_c$).

In addition to the incipient motion analysis for pools and for riffles, Ayres Associates conducted a flushing flow analysis to estimate the discharge required to flush surface sediment from pools. They assumed that the D_{84} of pool sediment was 2 mm and assumed a shear stress of twice the critical shear stress for the D_{84} would result in pool flushing. Their assumption for pool flushing flows was based on previous experience.

Results of the Ayres Associates analysis are only shown for the three most upstream sites (Sites 4 – River Mile[1] (RM) 128), 5 –RM 161, and 6 - RM 187) because the influence of Iron Gate Dam (RM 190) flows on bed conditions diminishes moving downstream from Iron Gate Dam as tributary accretions increase total flow (Table 3).

USGS – Holmquist-Johnson and Milhous (2010). The U.S. Geological Survey (USGS) conducted a study for the U.S. Fish and Wildlife Service to determine flushing flows required to improve and maintain quality spawning and rearing habitats for salmon, and to reduce the abundance of preferred habitats of *M. speciosa* (Holmquist-Johnson and Milhous, 2010). Field work for the Holmquist-Johnson and Milhous (2010) study was conducted in 2007. Just prior to data collection, three flow events occurred in 2006 where daily-mean flows at Iron Gate Dam exceeded 6,030 cfs (the two-year return period flow), but daily-mean flows in the previous six years (2000 – 2005) did not exceed 6,030 cfs.

Holmquist-Johnson and Milhous (2010) resampled sediment at the six study sites established by Ayres Associates (1999). Holmquist-Johnson and Milhous (2010) segregated samples into surface sediment, armor layer, and substrate (under the armor layer). The surface sediment was composed of silt-, clay- and sand-size sediment (i.e., fine sediment). The armor layer was composed of gravel-, cobble-, and boulder-size sediment (i.e., coarse sediment). The substrate was composed of a mix of sand-, gravel-, and cobble-size sediment.

Table 3. Ayres Associates (1999) incipient motion analysis results.

Incipient Motion Condition	Sediment Mobilization State (from Table 2)	Quantity	Site 4 RM 128	Site 5 RM 161	Site 6 RM 187
Pools Incipient Motion	Stable Bed	D_{50} – Median Grain Diameter (mm)	0.50	0.070	1.00
		τ_c – Critical Shear Stress (lbs/ft^2)	.00794	0.01100	0.0159
		Q_{c} – Critical Discharge (cfs)	2,300	2,600	2,500
Pool Flushing Flow	Surface Flushing	Q_{c} – Critical Discharge (cfs)	6,600	6,000	5,400
Riffles Incipient Motion	Armor Disturbance	D_{50} – Median Grain Diameter (mm)	86	86	86
		τ_c – Critical Shear Stress (lbs/ft^2)	1.01	1.01	1.01
		Q_{c} – Critical Discharge (cfs)	9,800	13,200	16,500

[1] Positions on the Klamath River are referenced by the distance in river miles measured from the river mouth and as shown on U.S. Geological Survey topographic maps.

Holmquist-Johnson and Milhous (2010) developed sediment entrainment discharge estimates using methods described by Milhous (1998). They defined four sediment mobilization states: Immobile Bed, Stable Bed, Surface Flushing, and Depth Flushing (Table 4). They estimated the sediment mobilization state for individual site conditions and discharges using the movement parameter β calculated using equation 3:

$$\beta = \frac{n^2 v^2}{1.492^2 d^{1/3} (G-1) D_{50}} = \frac{R S_e}{D_{50}(G-1)} \quad (3)$$

where:

β	is the dimensionless shear stress (movement parameter)
n	is Manning's n roughness coefficient
v	is cross section average velocity (ft/sec)
d	is cross section average depth (ft)
G	is the specific gravity of sediment (taken as 2.65)
D_{50}	is the median grain size (feet) of the bed armor later
R	is the hydraulic radius in feet
S_e	is the energy slope

The movement parameter (β) has the form of dimensionless shear stress and is analogous to the Shield's relationship. Increasing values of β imply increasing levels of shear stress applied to the river bed.

Sediment mobility states were then related to ranges of the movement parameter β (Table 4). The relationship between values of the movement parameter (β) and sediment mobility states are the same as employed in Milhous (1998). Values used to define sediment mobility states in Milhous (1998) are based on data collected at Oak Creek, Oregon in the early 1970's.

Holmquist-Johnson and Milhous (2010) employed the U.S. Army Corps of Engineers HEC-RAS hydraulic models developed by Ayres Associates (1999) and the sediment data they collected in 1997 to calculate movement parameter (β) values for discharges ranging from 1,000 to 50,000 cfs at each of the six Ayres Associates (1999) study sites. They fit a linear relation between movement parameter (β) and discharge at the Klamath River below Iron Gate Dam to estimate upper and lower discharge limits for Immobile Bed, Stable Bed, Surface Flushing, and estimate a lower discharge limit for Armor Disturbance.

Holmquist-Johnson and Milhous (2010) left a gap in their table between the upper limit of Surface Flushing ($\beta = 0.035$) and the initiation of Armor Disturbance ($\beta = 0.045$). Milhous (1998) defines Depth Flushing as the removal of fine material from within the substrate without Armor Disturbance and defines the value of the movement parameter (β) required to initiate Depth Flushing as 0.035. We adapted the Milhous (1998) study to set the range of the movement parameter (β) for Depth Flushing as 0.035 to 0.045.

Holmquist-Johnson and Milhous (2010) also computed the ratio between bed shear stress and critical shear stress required to initiate general movement of the armor layer for the range of discharges at the six study sites. They defined general movement of the armor layer as occurring when the boundary shear stress (τ_0) exceeds the critical shear stress for incipient motion of the armor layer (τ_c). Results of the Holmquist-Johnson and Milhous (2010) study found that the average critical discharge at Ayres Associates (1999) sites 4 (RM 128), 5 (RM 161), and 6 (RM

Table 4. Substrate movement state, movement parameter, and discharge limits for Klamath River below Iron Gate Dam (adapted from Holmquist-Johnson and Milhous 2010).

Substrate Movement State	Substrate Movement State Description	Movement Parameter β		Discharge (cfs)	
		Lower Limit	Upper Limit	Lower Limit	Upper Limit
Immobile Bed	No movement of surface sediment, armor layer or substrate. Deposition of suspended sediment absorbed into voids (until full).	0.000	0.009	0	2,500
Stable Bed	No movement of surface sediment, armor layer or substrate. Suspended sediment in water column remains in transport.	0.009	0.021	2,500	5,000
Surface Flushing	Movement of surface fine layers on 20-30% of bed.	0.021	0.035	5,000	8,700
Depth Flushing	Removal of in-filled fine sediment from armor layer.	0.035	0.045	8,700	11,250
Armor Disturbance	Movement of individual armor layer particles.	0.045	----	11,250	15,000
Armor Layer Movement	Reworking of armor and substrate layers ($\tau_0 > \tau_c$ of armor layer)	----	----	15,000	

187, the point at which $\tau_{0=}\tau_c$) was 15,000 cfs. Note that the average is based on ratio values of $\tau_{0/}\tau_c$ that ranged between approximately 0.65 and 1.45.

We combined the Holmquist-Johnson and Milhous (2010) estimates for discharges thresholds for Immobile Bed, Stable Bed, Surface Flushing, and Armor Disturbance with the estimates for discharge required to produce Depth Flushing (Milhous 1998), and with estimates for Armor Layer Movement to develop estimates for six sediment mobilization states for the Klamath River below Iron Gate Dam (Table 4).

Reclamation (2011). The U.S. Bureau of Reclamation evaluated sediment mobilization below Iron Gate Dam (Reclamation, 2011) as one component of numerous studies conducted to support the Secretarial determination process for the Klamath Basin Restoration Agreement and Klamath Hydroelectric Settlement Agreement (Department of Interior et al. 2013).

Reclamation (2011) developed a U.S. Army Corps of Engineers HEC-RAS model of existing conditions for the reach of the Klamath River from Iron Gate Dam (RM 190) to Happy Camp (RM 105). Model geometry was based on bathymetric surveys conducted in 2009 supplemented by LIDAR surveys conducted in 2010. Reclamation used the survey data to develop a triangulated irregular network (TIN) terrain model. Reclamation (2011) extracted 692 HEC-RAS cross sections from the TIN to develop a hydraulic model of existing conditions. Reclamation (2011) calibrated the HEC-RAS model using observed water surface elevation data and to gage data from Iron Gate Dam and at Seiad Valley (USGS 11516530, 11520500).

Reclamation (2011) analyzed stream gage records to develop flood frequency relationships for the USGS gages on the Klamath River below Iron Gate Dam (RM 190) and the Klamath River near Seiad Valley (RM 128) (Table 5).

Reclamation (2011) defined sediment mobilization states as follows:

- Under *Slight Mobilization*, there is a small, but measurable, sediment transport rate. The armor layer is only minimally disturbed and there maybe flushing of sand to a depth of the armor layer D_{90}.
- Under *Significant Mobilization,* there are many particles in motion and there is a significant sediment transport rate. Sand is mobilized from the interstitial spaces of the bed to a depth of twice the D_{90}. The armor layer is significantly disturbed.

Table 5: Flood frequency analysis for Klamath River below Iron Gate Dam (USGS Gage 11516530) and near Seiad Valley (USGS Gage 11520500 (Source: Reclamation, 2011).

Gaging Station		Klamath River below Iron Gate Dam	Klamath River near Seiad Valley
River Mile		190	128
Period of Record Used in Analysis		1961- 2009	1913 -1925 1952 -2009
Drainage Area (mi^2)		4,630	6,940
Discharge (cfs)	Median Flow	1,370	2,700
	Average Flood	7,978	28,569
	1.5 year return period	4,380	11,000
	2-year return period	6,030	17,600
	5-year return period	10,980	39,960
	10-year return period	15,610	56,540
	25-year return period	21,460	93,400
	50-year return period	26,280	131,000
	100-year return period	31,460	179,300

Reclamation (2011) developed a methodology to estimate the discharge required to generate *Slight Mobilization* and *Significant Mobilization.* Reclamation (2011) used hydraulic data from the HEC-RAS model and sediment data from their surveys to compute the Shield's parameter using equation (4), which is a re-arranged form of the Shield's relationship shown in equation (1):

$$\theta = \frac{\tau_g}{(\gamma_s - \gamma) D_{50}} \quad (4)$$

where:

τ_g is the grain shear stress

Reclamation (2011) computed the grain shear stress using results from the hydraulic modeling and methods that are detailed in Appendix J of their report.

Reclamation (2011) used the Parker Reference Transport method (Parker, 1990) to evaluate sediment mobility:

$$W^* = \frac{(s-1) g q_q}{\rho_s \left({\tau_g}/{\rho} \right)^{1.5}} \quad (5)$$

where:

s is the relative specific density
q_s is the sediment transport rate
τ_g is the grain shear stress
ρ_s is the sediment density
ρ is the fluid density
W^* is the dimensionless sediment transport rate.

The Parker (1990) method replaced incipient motion with a small, but measurable transport rate, where $W^* = 0.002$. The Shield's number that yields $W^* = 0.002$ is called the reference Shield's stress (θ_r).

Reclamation (2011) characterized *Slight Mobilization* as occurring when hydraulic conditions produced a Shield's parameter equivalent to the reference Shield's stress ($\theta = \theta_r$). Reclamation characterized *Significant Mobilization* as occurring when hydraulic conditions produced a Shield's parameter equivalent to 1.3 times the reference Shield's stress ($\theta = 1.3\theta_r$).

The value of 1.3 is equivalent to the ratio between the Holmquist-Johnson and Milhous (2010) movement parameter value of 0.045 (Armor Disturbance) and 0.035 (Surface Flushing). Thus, Reclamation's (2011) slight mobilization is equivalent to the Holmquist-Johnson and Milhous (2010) Surface Flushing and Reclamation's (2011) significant mobilization is equivalent to the Holmquist-Johnson and Milhous (2010) Armor Disturbance. Reclamation (2011) notes importantly that sediment transport increases as a continuous function, not a step function. There is a continuum of sediment transport movement between conditions where $\theta=\theta_r$ and $\theta=1.3\theta_r$ rather than an abrupt change in transport states.

Combining the HEC-RAS results with measured substrate characteristics, Reclamation (2011) developed estimates of the range of discharges required to achieve *Slight Mobilization* and *Significant Mobilization* in nine reaches of the Klamath River below Iron Gate Dam. Reclamation (2011) allowed for uncertainties in the value of the reference shear stress, creating a spread in discharge estimates. The median mobilization flow estimates are shown in Table 6. Reclamation (2011) related the discharge to return period using their frequency analysis (Table 5). Figures 2 and 3 replicates Reclamation (2011) figures showing the discharge and return periods estimates with error bars for initiating *Slight Mobilization* and *Significant Mobilization.*

Reclamation (2011) flow estimates for significant and slight mobilization vary considerably between the nine reaches defined in the study. The median flow estimate of 19,100 and 20,000 cfs required to produce slight mobilization in the reaches from Shasta River to Beaver Creek far exceed the median flow estimates for significant bed material mobilization from Bogus Creek to the Shasta River. The much higher flow required to initiate sediment mobilization between Shasta River and Beaver Creek might be undesirable because they would transport gravels out of the reaches located directly below the dam that are sediment starved due to trapping of sediment upstream of Iron Gate Dam. Development of environmental flow objectives should account for differences in geomorphic controls and sediment transport capabilities between reaches.

Reclamation (2011) states that the sediment entrainment analysis is not sufficient to predict the fraction of sand remaining after an environmental flow event. Such predictions would require more information about the surface and subsurface sand fractions as well as the sand supply in the reach and would require simulation of the sand budget and bed mixing during the event. Reclamation (2011) suggests that future studies of mobilization could be done to quantify the flows necessary to accomplish a certain level of sand mobilization in the Klamath River.

Table 6. Median discharges for slight and significant mobilization for Klamath River between Bogus Creek and Indian Creek (adapted from Reclamation 2011).

Reach	Slight Bed Material Mobilization Median Flow Estimate (cfs)	Significant Bed Material Mobilization Median Flow Estimate (cfs)
Bogus Creek (RM 189.6) to Willow Creek (RM 185.0)	9,800	15,900
Willow Creek (RM 185.0) to Cottonwood Creek (RM 182.1)	10,700	17,200
Cottonwood Creek (RM 182.1) to Shasta River (RM 176.7)	8,400	13,800
Shasta River (RM 176.7) to Humbug Creek (RM 171.5)	20,000	33,900
Humbug Creek (RM 171.5) to Beaver Creek (RM 161.0)	19,100	32,900
Beaver Creek (RM 161.0) to Dona Creek (RM 152.8)	5,800	10,100
Dona Creek (RM 152.8) to Horse Creek (RM 147.3)	5,900	9,700
Horse Creek (RM 147.3) to Scott River (RM 143.0)	6,500	10,400
Scott River (RM 143.0) to Indian Creek (RM 106.8)	15,300	25,500

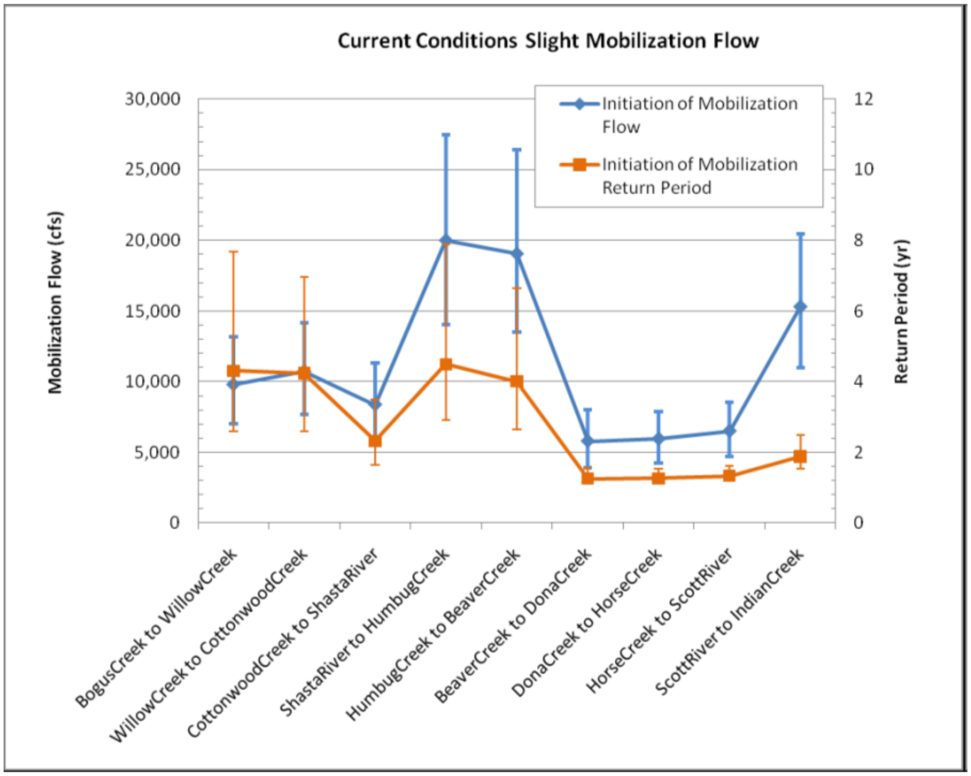

Figure 2: Slight bed material mobilization flow and return period for reaches downstream of Iron Gate Dam. (Reproduced from Figure 5-24, Reclamation, 2011).

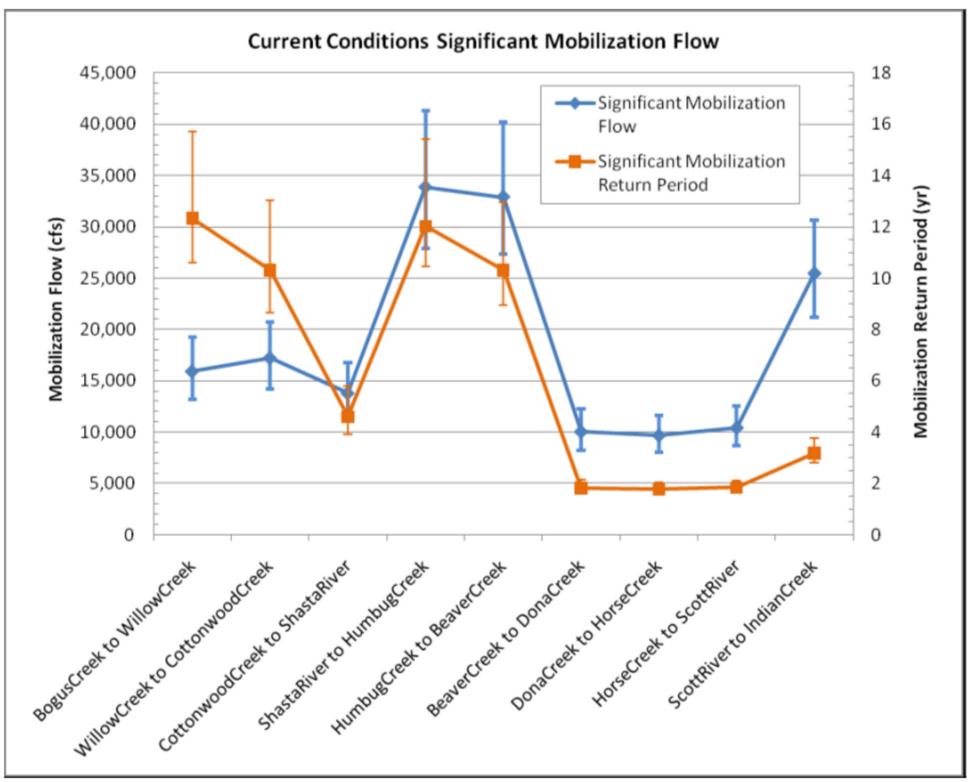

Figure 3: Significant bed material mobilization flow and return period on a reach averaged basis for reaches downstream of Iron Gate Dam. (Reproduced from Figure 5-25, Reclamation, 2011).

Comparison of Sediment Entrainment Analyses. Ayres Associates (1999), Holmquist-Johnson and Milhous (2010), and Reclamation (2011) used differing approaches to develop estimates of sediment entrainment. For purposes of comparison, we equate the Ayres Associates (1999) pool flushing flow with Holmquist-Johnson and Milhous (2010) Surface Flushing and Reclamation (2011) Slight Mobilization and we equate Ayres Associates (1999) riffle incipient motion with Holmquist-Johnson and Milhous (2010) Armor Disturbance and Reclamation (2011) Significant Mobilization (Table 7). We show the mean minimum Reclamation (2011) estimates for the Klamath River between Iron Gate Dam and the Shasta River confluence. Discharge thresholds in the Klamath River increase significantly downstream in the reach between the Shasta River and Beaver Creek reach because of its steep gradient, armor layer composed of immobile large cobbles and boulders, and occurrence of bedrock outcrops.

There is a spread in the estimates due to variances in the methods employed and the dates when channel substrate and channel conditions were evaluated, and the specific channel conditions at study locations.

Study Limitations. The three studies summarized in this technical memorandum provide useful estimates of the discharges required to mobilize bed sediment in Klamath River below Iron Gate Dam. There are some limitations resulting from the scale and scope of the studies:

- The Ayres Associates (1999) and Holmquist-Johnson and Milhous (2010) estimates are based on a hydraulic analyses that employed a limited number of stream cross sections collected at six sites that extended over 171 river miles. Only sites 4, 5, and 6 were used to evaluate conditions below Iron Gate Dam.
- All three studies developed sediment transport estimates using general sediment mobilization formulations. The estimates are not calibrated to direct observations of sediment transport in the Klamath River below Iron Gate Dam.
- All three studies used one-dimensional hydraulic models to develop estimates of hydraulic variables. The hydraulic variables extracted from the one-dimensional models are cross section averages and do not reflect the variability in flow velocities and depth across a river cross section, or across a river reach.
- The studies do not identify the mode of sediment transport (suspended or bedload).

Table 7: Comparison of sediment entrainment discharge estimates

Sediment Entrainment State	Discharge Estimate (cfs)					
	Ayres Associates (1999)		Holmquist-Johnson and Milhous, (2010)	Reclamation (2011): Bogus Creek to Shasta River		
	Low	High	Threshold Limit	Mean Minimum	Mena Median	Mean Maximum
Surface Flushing	5,400	6,600	5,000	6,900	9,600	12,900
Armor Disturbance	9,800	16,500	11,250	11,200	15,600	20,900

Additionally, the three sediment entrainment studies do not provide sufficient information to fully specify environmental flows to manage channel sediment. Wohl et al. (2015) and Schmidt and Wilcock (2008) recommend managing flow regimes below dams to produce a balanced sediment regime. Wohl et al. (2015) defines a balanced sediment regime as present when the energy of flow available to transport sediment is balanced by the sediment supply. Schmidt and Wilcock (2008) characterize a balance as occurring when the long-term transport of sediment out of a reach is equivalent to the long-term supply into the reach. Environmental flows developed to achieve a balanced sediment regime require information on sediment supply to a reach, sediment storage within a reach, and the effect of flow regimes on moving sediment out of a reach.

Additional Studies. Two additional studies bear mention because they provide the basis for further investigations into sediment mobility and developing environmental flow recommendations.

The U.S. Fish and Wildlife Service Arcata Fish and Wildlife Office (AFWO) and Oregon State University developed two-dimensional hydraulic models for three study sites in the Klamath between the Shasta and Scott Rivers (Wright et al. 2014; Alexander et al. 2016). The models are well calibrated and have been combined with statistical modeling for the purpose of analyzing distribution of *M. speciosa*. Modeling was combined with biological and physical observations made prior to and following major flows. These models could be adapted to calibrate sediment transport estimates and to tie physical outcomes of flushing flows to biological outcomes. Direct calibration of the flow required to achieve environmental flow objectives would improve the efficiency of potential water releases.

Malakauskas et al. (2013) performed flume experiments to evaluate flow requirements for dislodging *M. speciosa*. Their results identified shear velocity thresholds for dislodgement. This is another opportunity to directly relate measurable physical flow requirements to biological goals for disrupting *M. speciosa*.

Vegetation Disturbance and Geomorphically Effective Flow. Wolman and Gerson (1978) defined geomorphic effectiveness in terms of the ability of an event to alter the shape or form of the landscape. With respect to rivers, geomorphically-effective floods are described as creating a disturbance in the equilibrium river form (e.g., channel widening) that is followed by a recovery period where the channel readjusts to an equilibrium condition. Costa and O'Connor (1995) defined the energy produced by geomorphically-effective floods as a function of stream power (the product of the unit weight of water, discharge and energy slope) and flood duration for discharges above the incipient motion threshold for bed movement.

Floods are important mechanisms for maintaining channel form on rivers, including the Klamath River. During extended low-flow periods, riparian vegetation encroaches onto bar surfaces. Once riparian vegetation is established, it repeats a cycle of sediment trapping and channel narrowing and further encroachment of riparian vegetation into the channel (Ayres Associates 1999). Large, less-frequent floods of approximately a 10-year return period magnitude rejuvenate the Klamath River channel by reworking gravels on riffles, eroding channel banks and re-widening the channel, and removing substantial amounts of aquatic vegetation in the reach between Iron Gate Dam and the Scott River (Ayres Associates, 1999).

Holmquist-Johnson and Milhous (2010) estimated the threshold for general Armor Layer Movement at 15,000 cfs. Ayres Associates (1999) estimated the discharge required to rework gravel on riffles at between 9,800 and 16,500 cfs in the Klamath River between Iron Gate Dam and Seiad Valley. Ayres Associates (1999) suggested that discharges of approximately ten-year return period were required to rejuvenate the channel. Reclamation (2011) reported the ten-year return period discharge of 15,610 cfs as the approximate discharge needed to rejuvenate the river bed in the Klamath River below Iron Gate Dam.

We classify discharges that exceed 15,000 cfs in the Klamath River below Iron Gate Dam as geomorphically effective flows. This is an approximate estimate, but one which provides a general order of magnitude for a flow that will induce channel migration and create diverse geomorphic surfaces. Geomorphically effective flows remove accumulated riparian and aquatic vegetation, widen the channel where vegetation encroachment has narrowed the channel, and sort the gravel armor layer and substrate layer. The amounts of work done by geomorphically effective flows are dependent on duration and magnitude of discharges above the threshold value where Armor Disturbance occurs. After a geomorphically effective flow event, vegetation recovery, vegetation encroachment, and channel narrowing occur until the next geomorphically effective flow occurs.

Other Environmental Flow Considerations. There are several features of environmental flow releases for the Klamath River that require analysis.

Ramping Rates. Ramping rate is the rate of change in water flow released from a dam. Whiting (2002) notes than implementation of ramping rates in environmental flows are poorly addressed. Ramping rates that drop too rapidly can cause fish stranding and bank failures. Ramping rates that rise too quickly can create safety issues. Ramping rates can also be adjusted to meet other environmental flow objectives. For example, the Trinity River Restoration Program adjusts their ramping rates on environmental flow releases to encourage development of riparian vegetation.

Timing of Flows. Timing of environmental flows should consider how to minimize impacts to fish populations while identifying optimal times that flow may provide benefits, such as disrupting *M. speciosa,* in the case of the Klamath River. Timing should also consider how dam releases can interact to augment unregulated flood flows on local tributaries to cleanse fan deposits at tributary mouths to improve access by upstream migrant fish.

Duration of Flows. More analysis is required to evaluate the duration and shape of an environmental flow hydrograph. The duration should address how much sediment is available for transport and how much flow is required to cleanse the system. Specifying flow duration requires developing better information for implementing a balance sediment regime (Wohl et al. 2015) in the reaches of the Klamath River below Iron Gate Dam.

Need for Calibration. Monitoring and observation of bed mobility during flow releases are required to calibrate sediment and hydraulic assessments. Direct calibration methods allow for estimates of volume of sand and gravel that are mobilized (Kondolf and Wilcock (1996). Calibration work should be combined with monitoring observations of biological responses similar to the work of Alexander et al. (2016).

Sediment Mobilization Flows at Klamath River below Iron Gate Dam. In this section, we examine the occurrence of sediment mobilization flows for the Klamath River below Iron Gate Dam since construction of the dam in 1962. We downloaded daily-mean flow records from the USGS National Water Information System for USGS gage 11516530 Klamath River below Iron

Gate Dam for the period October 1, 1964 to September 28, 2016. Data are reported on a Water Year (WY) basis, which extends from October 1 to September 30 for all calendar years.

Occurrence of Sediment Mobilization Flows. We plotted the long-term hydrograph for the Klamath River below Iron Gate Dam from WY 1964 through WY 2016 with the discharge limits for the six substrate mobilization states defined in Table 2, as shown in Figure 4. The discharge limits are based on the sediment mobilization limits developed using the Holmquist-Johnson and Milhous (2010) and Milhous (1998) studies (Table 6). Although, the discharge estimates presented in Table 6 are at the lower range of the three sets of sediment mobilization estimates previously discussed, we chose to use the Holmquist-Johnson and Milhous (2010) and Milhous (1998) set because it is the only set that establish discharge ranges for all sediment mobilization states listed in Table 6. These should be seen as a conservative estimate of the flows required to mobilize sediment.

A visual analysis of Figure 4 shows that geomorphically-effective flow events (i.e., discharge > 15,000 cfs) are rare, occurring only five times between WY 1964 and WY 1997. Armor disturbing events are slightly less rare, occurring ten times between WY 1964 and WY 1997. The Klamath River below Iron Gate Dam has not experienced a geomorphically-effective or armor-disturbing event since the January, 1997 spill event. Surface Flushing and Depth Flushing events were common prior to WY 2000. Since WY 2000, Depth Flushing events occurred only during high runoff events in winter 2006 and during a controlled spill event in March 2016 (Figure 3).

Duration of Sediment Mobilization Flows. Because the effectiveness of sediment mobilization flows are a function of both sediment mobilization capability and the duration of flows capable of mobilizing sediment (Costa and O'Connor 1995), we evaluated the duration of sediment mobilization flows over time. We plotted the number of days per Water Year that daily-mean flows in the Klamath River below Iron Gate Dam fell in the range of a substrate mobilization state that transported sediment (Figure 4). We observed that the pattern of sediment mobilization can be split into two periods: (1) the period WYs 1964 to 1999, when sediment mobilization flows were common and (2) the period WYs 2000 to 2016 when sediment mobilizations flows were rare. From WYs 1964 to 1999, the average cumulative duration of Surface Flushing was greater than 22 days per water year. From 2000 to 2016, sediment mobilization flow occurred in only five of the 17 water years; and the cumulative duration of Surface Flushing flow exceeded five days in only one water year. We conclude that the effectiveness of sediment mobilization flows in the period WYs 2000 to 2016 substantially dropped from the period WYs 1964 to 1999.

Frequency of Immobile Bed Conditions. The *Immobile Bed* sediment mobility state is estimated to occur for flow rates of 2,500 cfs or less at the Klamath River below Iron Gate Dam. Flows released from the Iron Gate Dam carry suspended materials consisting of mineral content and organic material originating from in-reservoir algal blooms (U.S. Department of Interior and California Department of Fish and Game, 2012). During Immobile Bed conditions, suspended mineral sediment and organic materials released from Iron Gate Dam can settle and accumulate on the bed and are not re-suspended until the occurrence of flushing flows. Increase in the areas of fine-grain sediment and organic material deposits on the bed and channel margins is a concern because high densities of *M. speciosa* have been commonly observed on fine sediments that are most prone to mobilization. In addition, riparian and aquatic vegetation can colonize fine sediments, further narrowing the channel and degrading fish habitat conditions (USFWS and HVT 1999).

Immobile Bed conditions persisted during WYs 2000-2016, while immobile conditions were less frequent in WYs 1964-1999 (Figure 5). For 10 of the 17 years in the period WYs 2000-2016, Immobile Bed conditions persisted for over 90% of the year. In the period WYs 1964 -1999, Immobile Bed conditions persisted over 90% of the year in only eight of the 36 years.

Sequencing of Sediment Mobilization Flows. The occurrence of Surface Flushing flows in natural rivers is a frequent event. Flows that reach or exceed the top of bank (i.e., the bankfull flow) occur on a frequency of one to two years (Leopold, 1994). Dunne and Leopold (1978) define bankfull stage as the stream level that corresponds to the discharge at which channel maintenance is most effective. Schmidt and Potyondy (2004) employed 80% of the 1.5 year return period discharge as a first approximation of the Surface Flushing flow. Robinson (2007) recommended a two-year return period discharge as a first approximation of the Surface Flushing flow for sediment supply limited streams in Oregon. Note that the two-year return period discharge for the Klamath River below Iron Gate Dam (6,030 cfs) is in the range of estimates for sediment flushing flows listed in Table 7.

Effective channel maintenance flow regimes possess flows of sufficient duration and frequency to maintain channel morphology (Schmidt and Potyondy, 2004). Lack of sufficient flows causes loss of channel capacity. The lack of sufficient duration and frequency of flows in managed systems is also detrimental to system ecology (Annear et al 2004). Poff et al. (1997) attributes flow stabilization (i.e., maintenance of a stable flow without interruption by flooding events) as a cause of overall reduction of biological diversity and increases in presence of invasive species.

In the period WYs 1964 to 1999, the duration between Surface Flushing events below Iron Gate Dam was typically one to two years (Figure 6). There were two occasions, corresponding to a drought periods in the late 1980s and early 1990s, when the duration between Surface Flushing events reached almost three years and four years. The frequency of Surface Flushing events in the period WYs 1964 to 1999 is consistent with channel maintenance needs of natural streams. Since 2000, however, there have been three occasions when the duration between flushing events was approximately five years.

Between WYs 1964 and 2000, there were five geomorphically effective events (including the December 1964 flood) for the Klamath River below Iron Gate Dam (Figure 7). Duration between events ranged between two and 14 years. As of the end of WY 2016, there has not been a geomorphically effective event since 1997, a period approaching 20 years. Geomorphically effective flow events that remove vegetation encroachment and rejuvenate the channel used to be common, but are now rare.

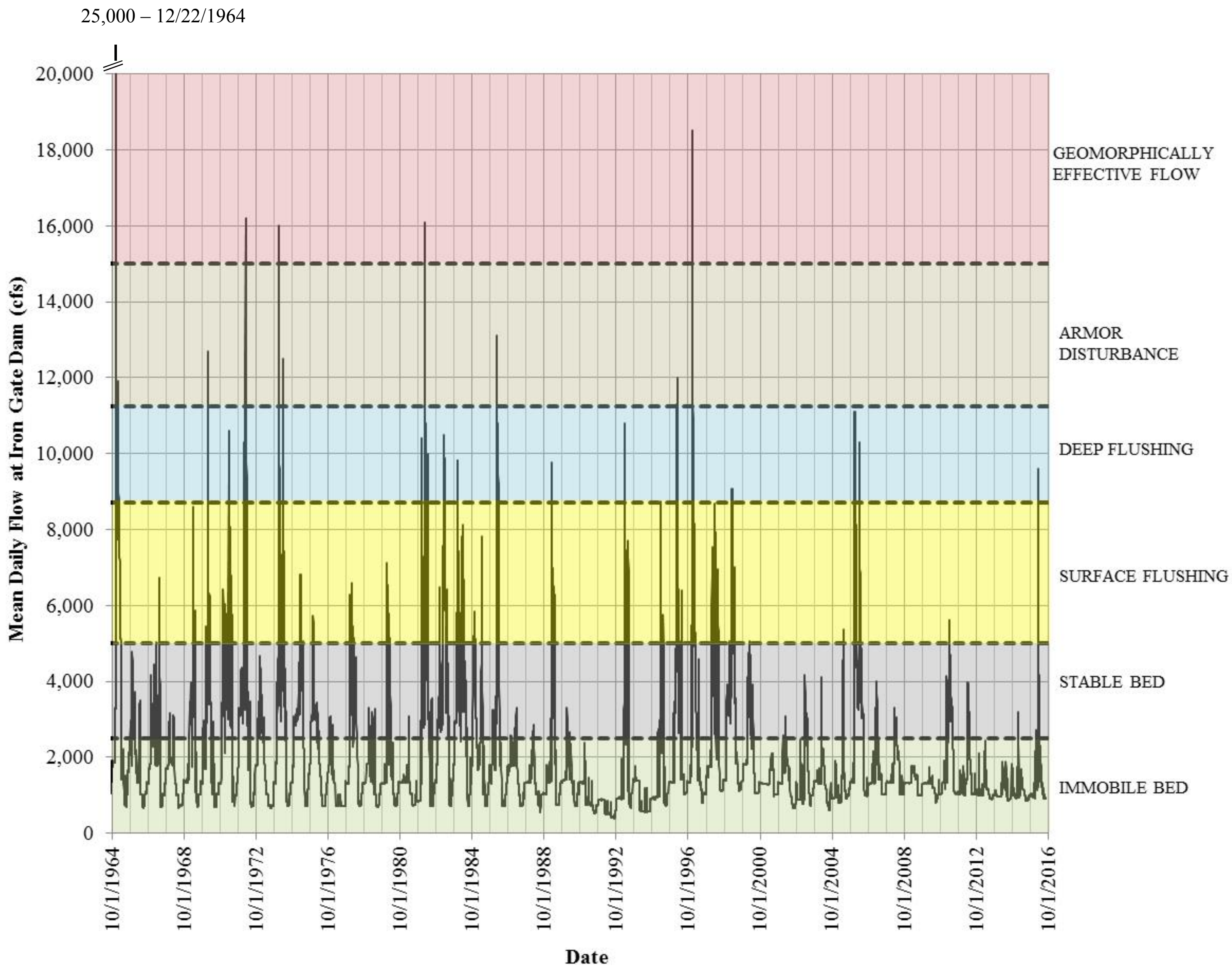

Figure 4: Daily-mean flow in cfs for Klamath River below Iron Gate Dam with substrate mobilization states. See Table 3 for definition of substrate mobilization states, Water Years 1964-2016.

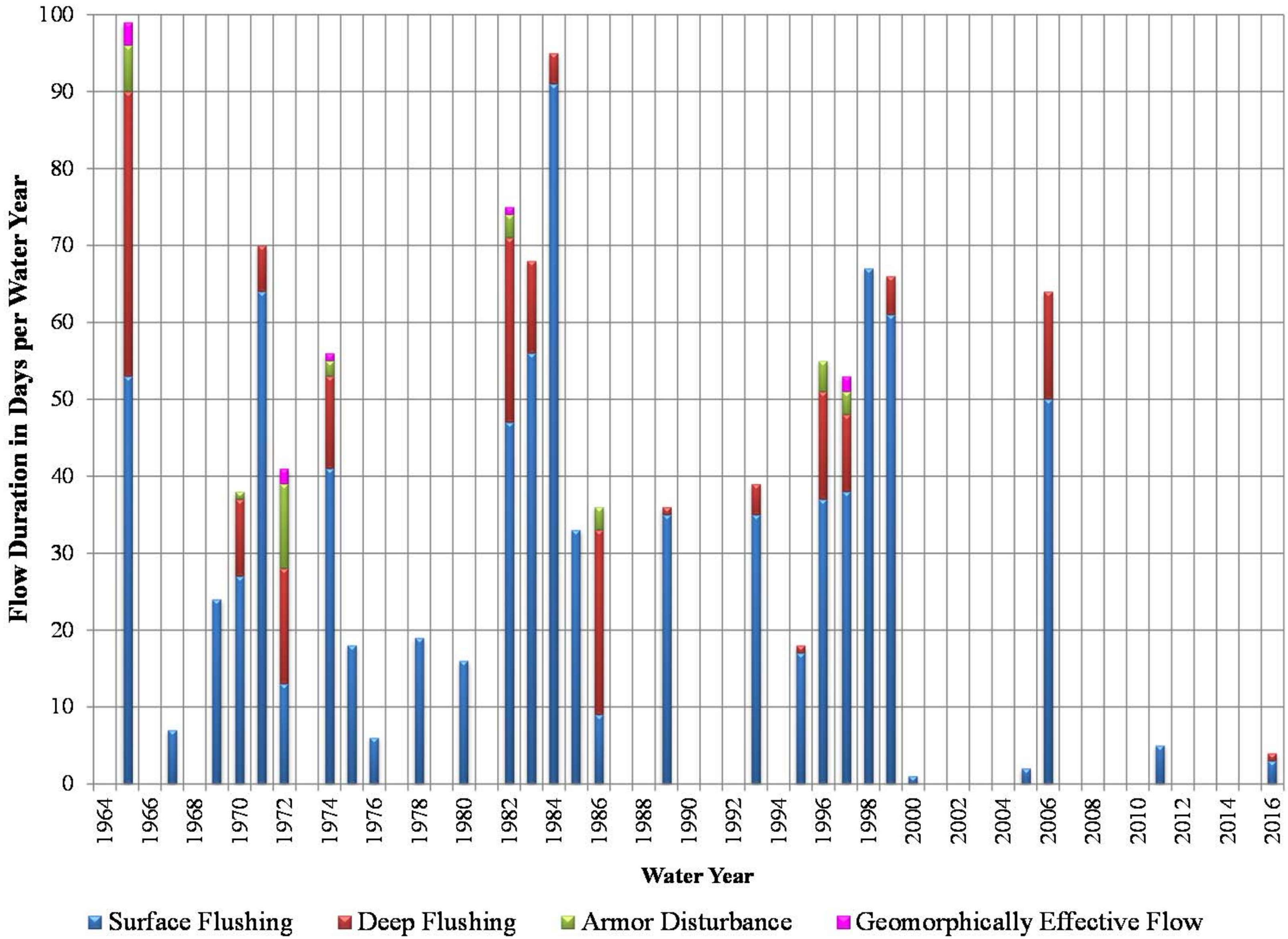

Figure 5: Duration of sediment mobilization flows in days per Water Year in the Klamath River below Iron Gate Dam Water for Water Years 1964-2016.

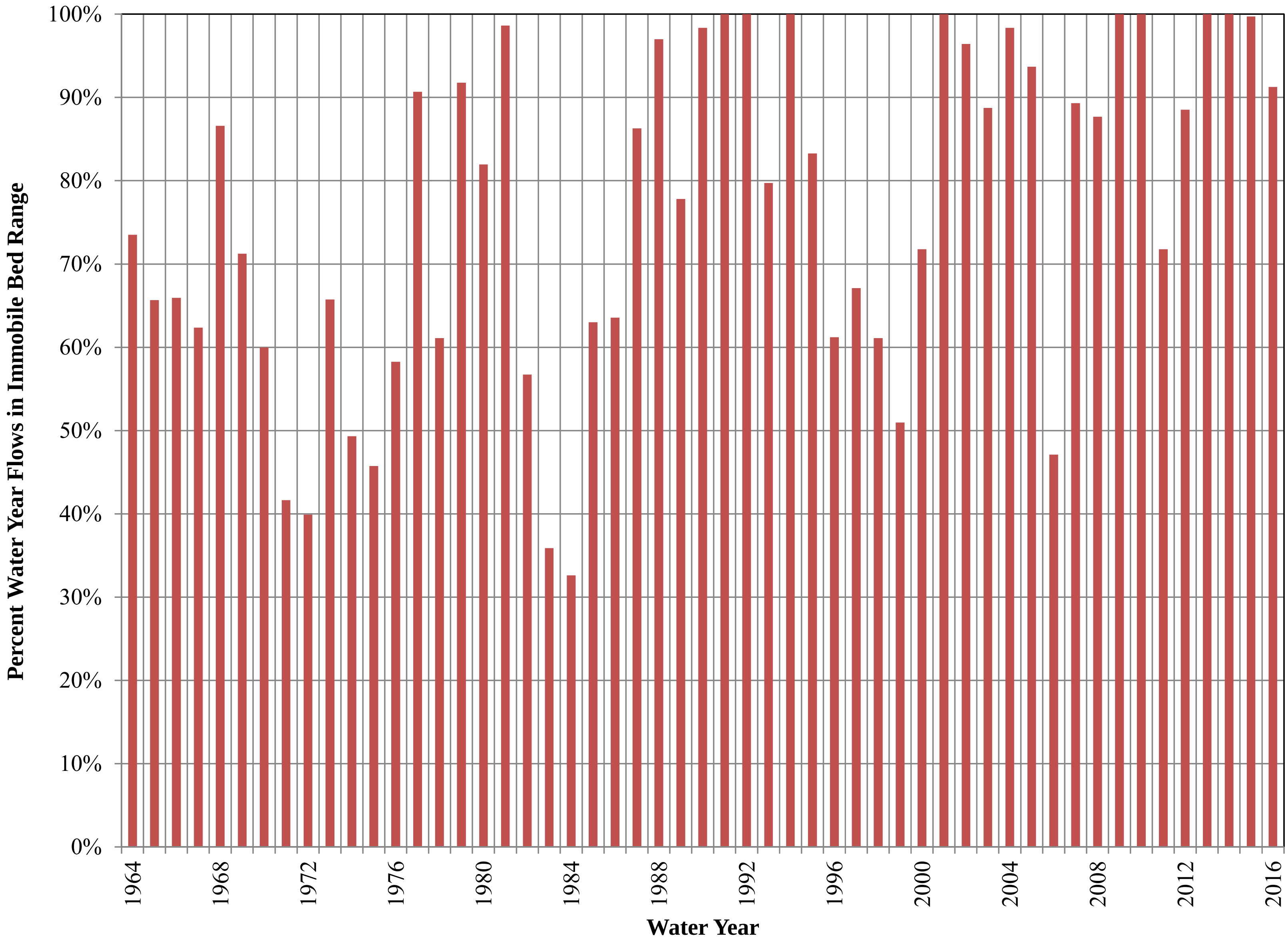

Figure 6: Percentage of Water Year Immobile Bed conditions occur in the Klamath River below Iron Gate Dam for Water Years 1964 -2016.

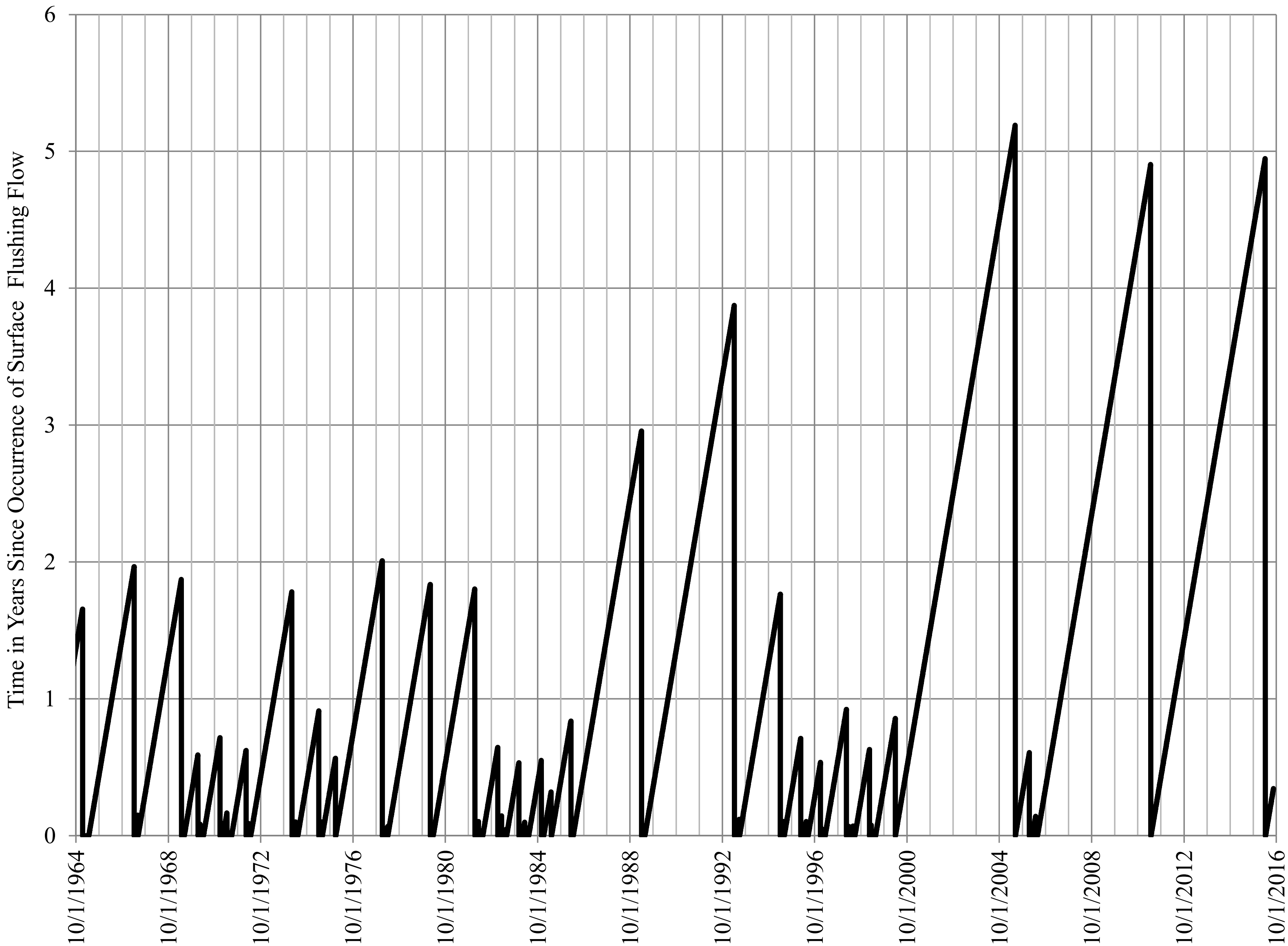

Figure 7: Time in years since occurrence of Surface Flushing flows in the Klamath River below Iron Gate Dam, Water Years 1964-2016.

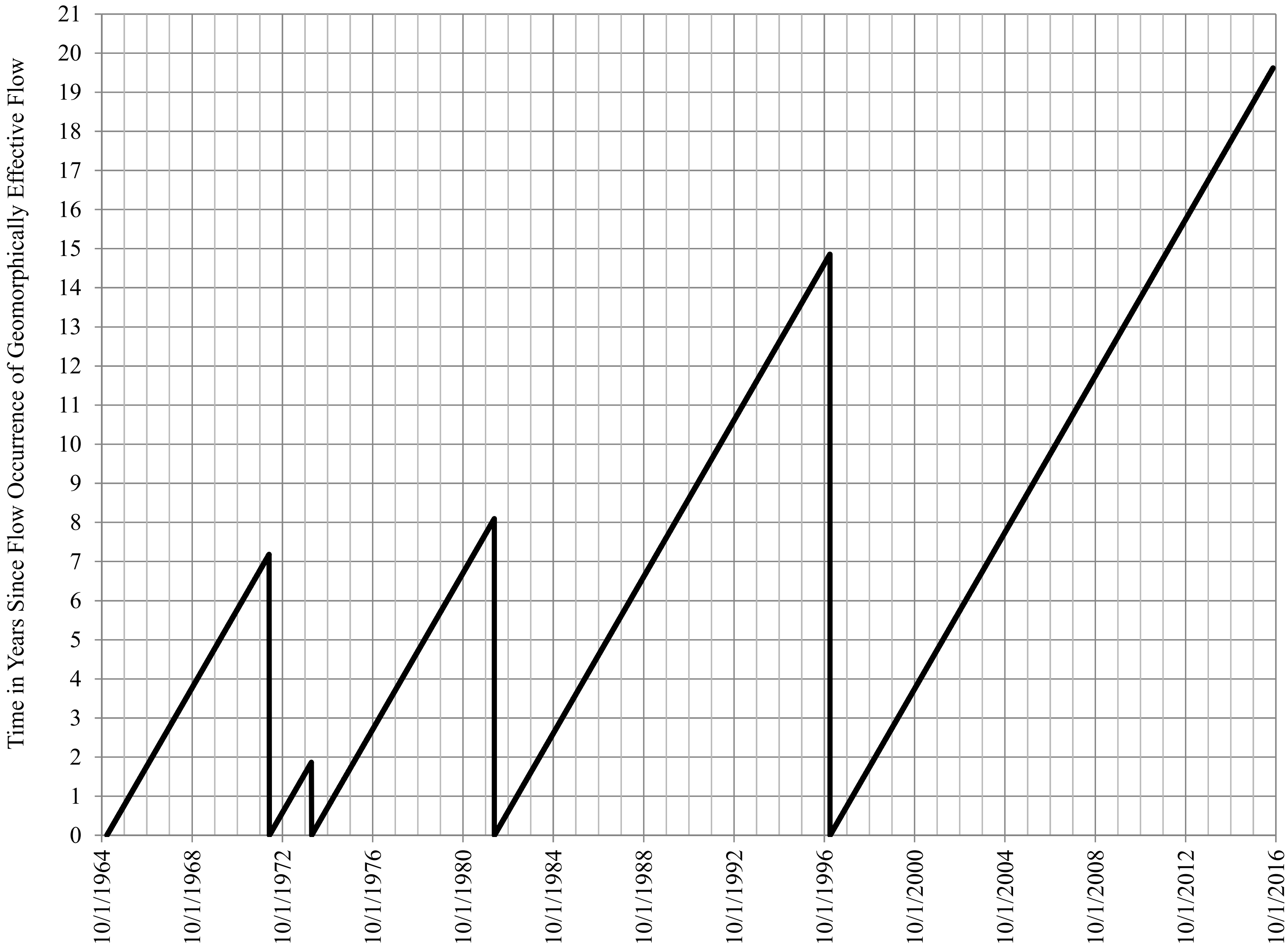

Figure 8: Time in years since occurrence of geomorphically effective flows in the Klamath River below Iron Gate Dam, Water Years 1964-2016.

Summary Guidelines.

- Environmental flows are developed by river managers to mitigate the detrimental impacts of dams and water diversions on river form and ecological functions. Environmental flow regimes designed to induce geomorphic changes are broadly divided into two categories, sediment maintenance or "flushing flows" used to modify substrate composition and channel maintenance flows intended to maintain channel form and floodplains.
- In developing environmental flow regimes, it is important to recognize conflicts in objectives and constraints on flow releases.
- There are three contemporary studies that estimated sediment transport thresholds in the Klamath River below Iron Gate Dam
- The sediment entrainment threshold estimates reported in the three studies varied due to differences in study methods employed and the dates when channel substrate and channel conditions were evaluated.
- Ayres Associates (1999) concluded that floods of approximately 10-year return period magnitude rejuvenate the Klamath River channel by reworking gravels on riffles, eroding channel banks, re widening the channel, and removing substantial amounts of aquatic vegetation in the reach between Iron Gate Dam and the Scott River.
- The 1.5-, 2-, and 10-year return period for the Klamath River below Iron Gate Dam was estimated by Reclamation (2011) to be 4,389, 6,030, and 15,610 cfs, respectively.
- The 10-year return period of 15,610 cfs reported by Reclamation (2011) is consistent with the findings of Holmquist-Johnson and Milhous (2010) who estimated the threshold for general Armor Layer Movement to be 15,000 cfs and that of Ayres Associates (1999) who estimated the gravel mobilization on riffles to occur between 9,800 and 16,500 cfs for the reach between Iron Gate Dam and Seiad Valley.
- We classify discharges that exceed 15,000 cfs in the Klamath River below Iron Gate Dam as geomorphically effective flows, which are occasional high flows required to maintain channel form and reduce riparian encroachment.
- Other important considerations in flow include ramping rates, timing, duration, and monitoring and calibration.
- From 1964 to 1999, the average cumulative duration of Surface Flushing flows exceeded 22 days per water year. From 2000 to 2016, the average cumulative duration of Surface Flushing flow exceeded five days in only one water year and no sediment mobilization flows occurred in 12 of the 17 water years.
- At flow releases less than 2,500 cfs below Iron Gate Dam, Immobile Bed conditions exist that allow suspended sediments to settle and accumulate on the bed, which are not re-suspended until flows that generate Surface Flushing occur.
- Growth of fine sediment deposits on the bed and channel margins is a concern because high densities of *M. speciosa* have been observed in such deposits. In addition, riparian and aquatic vegetation can colonize fine sediments, further narrowing the channel and degrading fish habitat conditions such as what has been documented on the Trinity River.

- From 1964 to 1999, the time between Surface Flushing events below Iron Gate Dam was typically 1-2 years, which is consistent with channel maintenance needs of natural streams reported in the literature. Since 2000, there have been three occasions when the duration between Surface Flushing events approached or exceeded 5 years.
- Between 1964 and 2000, 5 geomorphically-effective events occurred on the Klamath River below Iron Gate Dam, with the duration between events ranging between 2 to 14 years. There has not been a geomorphically-effective flow event, the events that remove vegetation encroachment and rejuvenate the channel, since 1997, in a period approaching 20 years.

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