Floated Debris from Girl Scout Camp on Upper Fairfax Creek (July 25, 2019)

Large Wood Debris Management Plan Recommendations for Fairfax Creek at the Sunnyside Flood Diversion and Storage (FDS) Facility

Fairfax, California
December 2019

MATT SMELTZER
C71671
Exp. 12/31/19
CIVIL

geomorph DESIGN

Prepared by:
Matt Smeltzer, P.E.
Geomorphologist/Hydrologist
CA Civil Engineer #71671

In Association with:
Paul Bigelow
Dr. Lee Benda, TerrainWorks

bigelow watershed geomorphology

Northern California 2100 Fourth Street, No. 154, San Rafael, CA 94901
Interior Alaska 129 Kristin Drive, Fairbanks, AK 99712

mobile/office 510-219-1064
www.geomorphdesign.com

Contents

List of Figures *Figures removed this version to separate file for transmittal purposes.*

List of Tables

1.0 Study Purpose

The purpose of this recommended large wood debris management plan is to provide technical background and outline practical assessment and information for the Marin County Flood Control and Water Conservation District (District) to consider in adopting a Large Wood Debris Management Plan (LWDMP) for properly managing risk to the FDS basin performance posed by wood expected to naturally float into the basin site from the Fairfax Creek watershed upstream.

2.0 Recommended Large Wood Debris Management Plan Measures

- <u>Large Wood Piece Size Reduction</u>. District implements pre-project, annual, and post-high flow monitoring of the 1,500-foot-long Management Reach downstream from the Baywood Canyon Road culverts to implement low-cost, minimum environmental impact, targeted piece size reduction for reducing or eliminating over time the number of large wood pieces that high flows would potentially mobilize and float into the basin during operations. The target-size large wood pieces are live upright, live-down, and dead-down trees that are between 18- and 36-feet-long. There are about 40-50 target-size pieces in the Management Reach. Most of the target-size pieces are live upright bay trees. Most of the remainder pieces are live-down but still rooted bay trees. Live upright and down bay trees can be severely pruned or topped without killing the tree. The recommended work is similar to “annual creek walk” and “creek clean-up” activities already routinely implemented by the County and municipalities on public and private properties in the same watershed.

<u>Large Wood Retention Structure</u>. District installs two columnar bollards spaced +/- 12-18 feet apart on the bed of Fairfax Creek along a cross-section within County property to catch large

floated wood debris (i.e., retention structure) upstream from the Sunnyside flood diversion and storage (FDS) basin weir, where the District may remove caught debris using crane or large excavator equipment.

3.0 Summary Findings for Technical Background

Potential Impacts to FDS Basin Operations. Small wood floated into the site during normal winter high flows is expected to pass safely through the diversion structure's 18-foot-wide gated culvert opening. During moderate floods not triggering basin operation, large wood debris floated into the site – i.e., longer than 18-feet-long – has the potential to come to rest at the gated culvert inlet. During high flow events triggering basin operation, small wood debris is expected to pass safely through the gated culvert and over the basin weir into the basin and over the dam spillway crest into Fairfax Creek downstream from site. However, should a large "key" wood piece float into backwatered site and lodge on the 200-foot-long basin weir or the 95-foot-long spillway, it could collect smaller floated wood pieces to form a wood jam that would potentially, by blockage, impact the basin's design hydraulic performance during actual future operations. This study does not evaluate potential hydraulic performance impacts for a range of basin weir and/or spillway blockage widths. Rather, it is assumed that a significant blockage of either or both the basin weir and/or spillway would substantially affect basin's design performance, thereby not reducing flood risk in downstream floodprone areas as much as it would in the absence of blockage by wood debris.

Natural Wood Debris Dynamics at the FDS Basin Site. The 4.1-km^2 (1.58-mi^2) Fairfax Creek watershed upstream from the Sunnyside basin site (site) exports relatively large volumes small wood and much lesser volumes of large wood by floating during intermittent and ephemeral flows through 18.2 km (11.3 mi) of channels (Figure 1). A three-year peak flow (Q_3) in December 2012 deposited 230 m^3 (300 cubic yards) of primarily small wood upstream from the 8-foot-diameter circular culvert at Glen Drive (Lockaby, 2019). Similar volumes of small wood debris are expected to enter the site during small floods, and much greater volumes during large floods. It is more difficult to estimate the threshold of movement and potential volume of large pieces – i.e., longer than 18-feet-long – entering the site. Large wood is not expected to pass through the 6-ft-wide and 12-ft-wide culverts under Baywood Canyon Road – large wood pieces may only yield from the “Management Reach” that is downstream from the Baywood Canyon Road culverts (Figure 1). Within this approximately 1,500-foot-long reach of mainstem Fairfax Creek, large wood may be exported to the site during high flows by mobilization of existing large down-live or down-dead wood in the stream, or of new large wood entering the reach during high flows by new bank erosion, tree toppling, or tree wind-throw. Field observations suggest several of the existing large live-down and dead-down pieces in the Management Reach probably entered the creek and/or were mobilized downstream but did not move completely through the management reach during the December 2005 flood. It is unknown what number of large pieces may have mobilized into and/or all the way through the basin site during that flood. It is notable that many of the large down pieces have already been reduced in size by chainsaw cutting. Large wood pieces longer than 36 feet – i.e., two times the estimated “bankfull” width – are considered too large to be mobilized and exported to the site during high flows. There are probably about 40-50 pieces of wood between 18- and 36-feet-long in the management reach, almost entirely comprised of existing upright live trees rooted on banks and adjacent top of bank areas.

Risk Management and General Recommendations. The risk to the basin’s hydraulic and safety performance posed by these 40-50 live upright, live-down trees, and dead-down trees cannot be accurately estimated. There are not reliable methods for estimating what “threshold” flood peak flow would be high enough to move the existing down large wood pieces into the site, or be high enough to trigger widespread bank erosion to put a number of existing upright trees in the flood flowing creek, or then possibly floating them into the site. Neither are there reliable methods for modeling the potential for large pieces floating into the site to come to rest on the basin weir, spillway crest, or gated culvert opening. Potential for lodging of one "key" large wood pieces on the facilities to then gather enough other wood debris to substantially reduce basin performance is also not predictable. The premise of this study is that wood debris floated into the site poses a risk because of its potential to reduce basin performance. Findings summarized above suggest that natural wood debris export to the site poses a low, possibly negligible level of risk during small and moderate floods, and a higher of risk during large floods. The risk is possibly significant during very large floods.

Accordingly, the recommended management measures are selected for reducing the potential for large wood pieces to enter the basin site during moderate to large floods. Perhaps the first priority is to implement a large wood piece size reduction program for reducing and possibly eliminating over time the number of estimated problem-sized pieces that have a reasonable potential to be mobilized into the site during moderate to large floods. Another effective and "fail-safe" measure would be to install a retention structure – i.e., row of widely spaced columnar steel bollards along a creek cross-section – to catch only large sized floated wood pieces before they enter the site during floods.

Both of these recommended management measures would entail environmental impacts that may not have been quantified and analyzed by the SAFRR Project EIR. The recommended piece size reduction work would occur on private property. The recommended retention structure would be located entirely within County property. These and other specific considerations for implementing both of the recommended measures are outlined in the below sections of this report.

The District may elect to implement one or both of the recommended management actions to reduce risk posed by movement of wood debris into the FDS Basin site by an amount that balances initial and ongoing implementation costs with the estimated value of risk reduction. In general, the District is recommended to consider implementing an aggressive version of the piece size reduction work on upstream private property if it elects not to install the recommended "fail-safe" retention structure. Similarly, should the District elect not to implement the recommended piece size reduction work, perhaps, for example, because of the work needing to occur on private property, then it should more strongly consider installing the retention structure. Implementing both measures would achieve the higher level of risk reduction.

4.0 Recommended Measure 1: Large Wood Piece Size Reduction

This plan recommends that the District implement piece size reduction work as its primary large wood debris management measure. The work includes work pre-project, annual dry season, and as-needed post-flood wet season maintenance work throughout the 1,500-foot-long management reach. In each maintenance work session, all live upright trees, and live-down and dead-down tree debris and large wood pieces in the 18- to 36-foot-long target-size range that are in the creek or within 10 feet landward from the top of bank will be documented. Selected pieces would be chainsaw-cut into two or more pieces not each not more than 12-feet-long, according to selection criteria for meeting as applicable any environmental permit conditions, landowner requirements and preferences, professional judgement and other factors. Appendix A provides an inventory of all large dead wood pieces and Appendix B provides an inventory of both dead and live wood pieces occurring within the bankfull channel of the study reach. This July 2019 inventory listing the diameters and lengths of existing live and dead pieces in the part of the management reach upstream from the FDS basin site.

Landowner cooperation. The bed and banks of Fairfax Creek in the Management Reach occurs on multiple private properties. Tree and debris cutting work would require permission from the individual landowner. Many of the existing live-down and dead-down large wood debris pieces have been chainsaw-cut, so it appears likely that most of the affected landowners would cooperate with the District to implement work that is similar to what they have been undertaking themselves or hiring contractors to implement.

Avoid and Minimize Habitat Impacts. Most of the estimated 40-50 target-size large wood pieces are live upright bay trees. Most of the remainder pieces are live-down bay trees still rooted to the bank. Fewer are dead-down bay and maple trees. Live upright and down bay trees can be severely pruned or topped without killing the tree. The recommended work is similar to “annual creek walk” and “creek clean-up” activities already routinely implemented by the County and municipalities on public and private properties in the same watershed. Ongoing routine tree and debris pruning and removal work occurs in perennial, steelhead-bearing sections of the creek in the downstream part of the watershed. Fairfax Creek does not provide quality steelhead habitat, and access to Fairfax Creek is prevented by 500+-foot-long bypass box culvert between Bolinas Avenue and receiving San Anselmo Creek. The Management Reach dries up early each spring. Piece size reduction work can be completed without substantially reducing the supply of large wood debris in Fairfax Creek downstream from the FDS basin site either by leaving reduced-size pieces on the creek bed and banks in the Management Reach for natural movement through to downstream from the basin, or by removing pieces from the channel and placing them in the channel downstream from the basin site.

Mitigate Unavoidable Impacts. Any tree mortality or tree removal caused by the work may need to be mitigated, such as by compensatory riparian tree container plantings, if feasible considering the shady conditions and lack of irrigation at the site, or contribution to riparian tree establishment work within the same watershed.

Annual Monitoring Report. An annual report should be prepared documenting the inventory of target-size large wood pieces identified and piece size reduction work performed in the Management Reach during each maintenance work session (pre-project, annual dry season, and as-need post-storm wet season).

One-Time Pre-Project Implementation Cost. The ballpark-estimated cost for implementing the piece size reduction work in the 1,500-foot-long Management Reach for the initial pre-project maintenance is about $25,000 (more if cut pieces are removed from the channel and placed back in the channel downstream from the basin site). This cost does not include permitting and compensatory mitigation planting costs, if applicable.

Ongoing Annual Average Implementation Cost. Annual recurring costs for monitoring and as-needed piece size reduction work, including reporting, are anticipated to average about $10,000.

5.0 Recommended Measure 2: Large Wood Retention Structure

The recommended piece size reduction program would reduce the supply of readily-mobilized down-dead and down-live large wood pieces on the creek bed. And, depending on how aggressive the piece size reduction work is implemented, it would reduce the number of live upright trees between 18- and 36-ft long that may enter the creek during storm flows by bank erosion or wind-throw. However, it would not entirely mitigate the potential supply of whole live standing trees which may be recruited by severe bank erosion during large and very large floods. Because there is expected to be as much as or more than 690 m^3 (900 cubic yards) of small and fine wood debris delivered to the FDS basin by the upper watershed during these very high peak flow events, the potential remains during rare events for a previously live standing tree to enter the stream by bank erosion and float into the basin, lodge as a “key” piece on the basin weir or spillway crest, and gather rafts of small and fine debris to form a substantial jam. Therefore, it is recommended that the District nearly completely mitigate this potential by installing a large wood debris retention structure to catch large wood debris, such as a during-flood recruited whole tree, upstream from and before it floats onto and potentially lodges on the basin weir and diversion structure.

Large wood debris retention structures are typically comprised of a row of vertical posts spanning across the entire width of the channel with a maximum spacing between posts set and top elevation above the design flood water surface elevation for catching and holding large debris pieces and jams of smaller debris racked on large pieces during floods. Figure 10 shows some examples of wood debris retention structures used in Europe. Bradley et al. (2005) describe debris control structures used for bridges and culverts in the U.S.

Specifically, it is recommended that the District installs two columnar bollards spaced +/- 12-18 feet apart on the bed of Fairfax Creek along a cross-section within County property that is upstream from the basin weir, near the existing driveway bridge so that the District may remove caught debris using crane or large excavator equipment operated from the existing driveway bridge.

Design Considerations. A retention structure would significantly reduce the potential for a substantial rare-event jam from forming on the basin weir and the spillway crest, by forcing it – as a fail-safe measure – to form on the retention structure. If one or more large live trees are caught on the structure, there would likely be sufficient export of small and fine debris from the upper watershed to “rack” on the large pieces to form a jam nearly spanning the entire width of the creek. For example, the flow top width at the driveway bridge cross-section vicinity is 40-45 feet, and pieces up to about 36-feet-long are expected to be exported to the site during large and very large floods. In such a scenario, the altered hydraulics at the structure may cause excessive deposition of gravel on the channel bed, increased bank erosion pressure on the channel banks at either or both sides of the structure, or incrementally higher flood water surface elevations upstream. These potential rare-event impacts are likely mitigable through design analysis and likely preferable to hydraulic and safety performance impacts of jam formation on the basin weir or spillway crest downstream. The hydraulic backwater effect resulting from basin operations extends upstream from the recommended retention structure location. Therefore, it follows generally, that a jam formed at the retention structure would not substantially increase upstream flood water surface elevations or coarse sediment deposition. As well, the channel-averaged velocities reduced by the backwater effect would buffer local impacts on bank erosion pressure caused by a jam concentrating surface flow on either side of the creek.

Should there be a debris blockage during a small or moderate flood flow when or before the basin is operated, there may be more pronounced impacts on upstream flood water surface elevations, but not to the extent to cause elevations higher than planned for under basin operations. Resulting local coarse sediment deposition and bank erosion pressure impacts may be more pronounced. Bank erosion protection planned for the larger FDS basin project would likely be sufficient, but may need to be augmented depending on the location of the retention facility, and the final details for the bank erosion protection in design development.

This study did not review Quincy Engineers' analysis of the structural capacity of the existing bridge which should be confirmed and selection of the structure location determined in conjunction with confirmation of appropriate equipment access and bridge capacity.

Landowner cooperation. The recommended location for the retention structure is within safe equipment reach from the existing private driveway bridge, entirely within County property. Landowner cooperation through outreach and sharing of design analysis may be needed to ensure property owners immediately upstream from the County property that the hydraulic impacts of a potential jam would not surcharge upstream water surface elevations any more than planned for as resulting from normal basin operations.

Avoid and Minimize Habitat Impacts. The permanent environmental impacts of installing two vertical columnar 12-inch-diameter steel pipe bollards on the Fairfax Creek bed are very small – approximately 1 lineal foot, 2 square feet, and 0.3 cubic yards of permanent fill would be placed below the ordinary high water line. The temporary construction impacts would be subsumed in those of the overall FDS basin facilities construction. Reliably dry channel bed conditions prevail at the site so there would not be temporary construction impacts to fisheries.

Mitigate Unavoidable Impacts. Unlikely required.

Annual Monitoring Report. Unlikely required.

One-Time Pre-Project Implementation Cost. The ballpark-estimated construction cost to install two 15-foot-high (exposed) 12-inch-diameter steel pipe bollards drilled and/or driven approximately 20 feet into the bed of Fairfax Creek (or less, depending on geotechnical analysis) is less than about $35,000. Combined with design and permitting, the one-time implementation cost of the retention structure may be as much as about $60,000.

Ongoing Annual Average Implementation Cost. Cost to remove debris caught on the retention structure is expected to be zero in most years, and less than $10,000 after rare events.

Residual Risk. Because the retention structure would be purposely located upstream from the basin weir facility and close to the existing driveway bridge, there would remain numerous existing live standing trees between the bridge and the spillway which may enter the basin during storm flows before or during basin operations. Moreover, in rare circumstances, large wood pieces could float through past the retention structure if oriented in a s stream-lined direction. Therefore, the District should develop a contingency plan for safely removing large wood debris from the basin weir or spillway during basin operations. Such a plan would be even more critical if the District elects not to implement the recommended retention structure.

As well, small wood is expected to continue to pass freely into the site whether or not the District implements the recommended retention structure and/or the piece size reduction work. Accumulations of small debris are not expected to be large enough to significantly reduce basin performance, but yes, the District should also anticipate removing accumulated small wood debris from the basin weir and dam-spillway crest surfaces during basin operation events as needed to prevent unforeseen hydraulic performance impacts and, of course, also as needed for maintenance after high flow events.

6.0 Estimating Wood Debris Export from the Fairfax Creek Watershed

The recruitment, storage, and transport of wood debris are natural processes in river systems with riparian vegetation. Where creeks and rivers intersect infrastructure (diversions, culverts, bridges, reservoirs, etc.), the supply of small to large wood debris can impact their function (Moulin and Piegay 2004, Bradley et al. 2005). To better manage wood debris supplied to such facilities requires information on the rate of production, storage, and transport of wood debris from the upstream watershed (e.g. Senter et al. 2017). To help understand and better manage wood debris supplied to the Sunnyside FDS basin on Fairfax Creek, this study evaluates the potential wood exported from the upstream watershed and recommends wood debris management measures for minimizing potential effects on basin performance.

This study:

1. Estimates the wood export (volume per time) from the basin during large floods (e.g., multi-decade to 100-year flood) to inform evaluation of impacts to Sunnyside FDS basin performance. For example, during floods large pieces could lodge on the spillway or basin weir, subsequently collecting smaller wood pieces and forming a wood jam affecting the intended hydraulics of the structure.

2. Characterizes the wood volumes and piece lengths in the channel from the FDS basin upstream to the nearest culverts, as large pieces in this reach have a higher potential to impact the diversion structures. The upstream culverts can limit the passage of long wood pieces from the upper watershed.

3. Recommends additional methods to characterize wood export and monitoring of in-stream wood conditions, and potential wood management strategies (e.g., wood debris retention structures, wood piece size reduction and removal) to reduce potential failure of the diversion structure during large floods.

Wood Export. Preliminary results of this brief study indicate that as much as or more than about 300 cubic yards of floated wood debris may enter the FDS basin site during winter peak flows meeting or exceeding the 3-year peak flow, and probably as much as 3 or more times that amount in an extreme event.

To help manage wood debris supplied to the Sunnyside flood diversion and storage (FDS) basin on Fairfax Creek, this study evaluates wood export from the upstream watershed and wood debris management options. We constructed a wood budget to estimate wood exported from the basin during small and large floods. The wood budget "model" was developed specifically for this study using a combination of an attributed GIS stream layer, wood recruitment rates, wood storage, and wood transport estimates based on wood mobility (see details later). The 3-year flood event (Q_3) in December 2012 exported an estimated 230 m^3 (300 yd^3) of wood debris forming a jam at a culvert inlet downstream of the FDS basin (Lockaby 2019, see details later). The wood budget model used to predict wood export was calibrated to match this export volume for a small flood. Predicted small and large flood wood export volumes at the Sunnyside FDS basin are 182 and 352 m^3 (238 - 460 yd^3), respectively, or roughly 23 to 46 dump truck loads of wood.

6.1 Background

6.1.1 Fairfax Creek Watershed

At the Sunnyside FDS basin, Fairfax Creek watershed drains an area of 4.1 km^2 (1.58 mi^2) from roughly 18.2 km (11.3 mi) of channels with ephemeral stream flow (Figure 1). Mean annual precipitation in the basin is 112 cm yr^{-1} (44 in yr^{-1}) (PRISM 2019). Riparian stands are comprised of hardwoods, predominately California bay laurel (*Umbellularia californica*) and willow (*Salix lasiandra*). The basin valley floor is comprised of Quaternary alluvial and colluvial fill and the underlying basin geology consists of Cretaceous Franciscan Mélange (Graymer et al. 2006), heavily prone to mass wasting in steep and convergent terrain (Wentworth et al. 1997, Ellen et al. 1997). Fairfax Creek channels are generally incised, down to bedrock in some areas, and are now widening in areas without revetted banks. Aggradation associated with the active channel widening is forming a new flood plain inset within the historically incised channel. This incised channel evolution follows the typical response to base level change or disturbance (e.g. Schumm et al. 1984, Schumm 1999) observed in many San Francisco Bay Area channels (e.g. Bigelow et al. 2016).

6.1.2 Sunnyside FDS Basin

The Sunnyside FDS basin is designed to reduce peak flows in flood prone areas downstream. A flow diversion and overflow structure constructed across Fairfax Creek controls how and when water is diverted into the basin. The diversion structure consists of a concrete spillway overlying a 5.5 m-wide by 1.8 m-high (18 ft-wide by 6 ft-high) culvert with a radial gate. During incipient flooding, the gate lowers to a partially closed position (0.4 m-high opening [1.3 ft]) to allow bypass flow. Flood water behind the diversion structure rises until it reaches the top of the basin weir, and then flows into the FDS basin. When flood water further rises to the top of the diversion spillway, flood water flows over the spillway and continues downstream. Backwater from the FDS operation can extend up to 320 m (350 yd) upstream.

6.1.3 Wood Export

Understanding how wood moves in a channel network is a key component in estimating wood export from a watershed. Numerous factors govern wood transport. Transport of large logs tend to occur when the pieces are shorter than bankfull width (Lienkaemper and Swanson 1987; Nakamura and Swanson 1993). For small branch size pieces, channel width may be less relevant to wood transport efficiency. Wood transport is affected by stream power and flow magnitude, so large floods transport more wood debris (Haga et al. 2002), where the largest wood export occurs during infrequent high flows (Fremier et al. 2010). Some wood can be mobilized at less than bankfull flows, threshold transport then increases linearly with discharge, and wood transport capacity is likely maximized at bankfull flows when overbank flow is reached (Kramer and Wohl 2017). Wood diameter can be a good predictor of mobilization (Haga et al. 2002). Iroume et al. (2015) found that pieces transported during average floods had diameters less than half bankfull depth (also see Braudrick and Grant 2000, Welber et al. 2013). Others have found that as the ratio of piece diameter to flow depth approach one, mobility is enhanced (Haga et al. 2002). Once wood is mobilized, there is generally no consistent relationship between piece size and travel distance. Reliable prediction of wood export remains an open question, as knowledge of entrainment and transport processes is still limited by a lack of accurate field data (Mazzorana et al. 2017), in part due to the inherent difficulty of such measurements during floods.

6.2 Methods, Modeling, and Field Observations

6.2.1 Modeling Wood Recruitment and Export

To estimate stream wood exported from Fairfax Creek basin, we use a wood budget framework (e.g. Benda and Sias 2002, Benda et al. 2018). A wood budget is similar to a sediment budget, simplified here for this brief watershed scale study:

$$W_o = W_r \pm \Delta W_s \qquad \text{(Equation 1)}$$

where over a given time frame, W_o is the the wood volume exported from the basin; W_r is wood volume recruited into the channel network from the riparian stand by mortality, bank erosion, or mass wasting (m^3/time); and ΔW_s is the change in wood volume stored in the channel. In this approach, we do not account for loss of wood from decay. The wood budget constructed for this study (see more details later) provides more robust estimates of wood export with a fuller understanding and accounting of processes influencing wood recruitment, storage, and transport compared to rapid evaluations of wood export that simply measure wood storage in representative reaches and extrapolate those values to the entire watershed (e.g., Bradley et al. 2005, Diehl and Bryan 1993).

Both living and dead wood are stored in the Fairfax Creek channels (e.g. Opperman and Merenlender 2007). Living wood is recruited to the channel by bank erosion or landslides, but the roots remain attached to the channel banks. Dead wood is not rooted and consequently much more mobile. Live wood can be eroded and mobilized in large floods. With these differences in mind, we estimated wood export from the basin for small and large floods as summarized on Figure 3 and described below.

Export during small floods on the scale of Q_3. Exported wood includes all dead wood (both in jams and between jams) for mobile pieces, plus the annual recruitment rate. The annual recruitment rate reflects both the rate at which wood is recruited to the stream and the rate all live wood in the stream breaks down to more mobile dead wood. This approach is reasonable if dead wood behind jams moves during bankfull flows. A recent wood transport review and synthesis by Kramer and Whol (2017) suggests that wood in jams moves during high flows, and jams reform on the receding limb, often in the same place (e.g. Curran 2010).

In this conception of wood export for small floods, all mobile dead wood gets out, the live wood stays. To maintain the mass balance of wood storage (Equation 1), wood export for annual flows (Q_1) should be similar to annual wood recruitment, while wood export for small floods (Q_3) should be a bit higher than annual wood recruitment (i.e. small net loss from wood storage).

Export during large floods (multi-decade to 100-year flood, Q_{large}). Exported wood includes all mobile dead and live pieces, the annual recruitment rate, a bank erosion recruitment rate, and a proportion of inset flood plain or hillslope overbank wood. Large floods are on the scale of multiple decades up to Q_{100}. This is reasonable based on our surveys of wood recruitment in Fairfax Creek. The oldest recruited trees date roughly back to the 2005 flood (Q_{100}), indicating that all the previous recruited live wood was scoured by bank erosion and transported in this event, and substantial amounts of new live wood were recruited to the channel by bank erosion. In this conception of wood export for large floods, all mobile live and dead wood gets out, and there's a substantial net loss of wood storage from the channel (Equation 1).

6.2.2 Field Measurements, Observations, Parameter Calculation

Wood Export Observation. We obtained one observation of wood export (W_o) from the Fairfax basin, where an estimated 230 m^3 of wood collected behind a plugged culvert (2.4 m diameter) under Sir Francis Drake Blvd at Glen Drive (Figure 2) in December 2012. Peak flow at the Ross gage on Corte Madera Creek was 78.4 m^3/s (2,770 ft^3/s) on December 2, 2012, a 3 or 4-year flood event (Q_3) as interpolated from the flood frequency curve for Ross gage (Stetson Engineers and geomorphDESIGN 2009). Blockages at bridges and culverts typically occur when whole trees or large pieces obstruct the inlet, then all subsequent pieces pile up (Lockaby 2019). The culvert is approximately 640 m downstream from the Sunnyside FDS basin and drains an area of 4.8 km^2 (1.85 mi^2) (Figure 1). We use this observed export volume to check and adjust (calibrate) our estimates of wood export based on surveyed wood recruitment and wood storage using Equation 1. The difference (%) between the predicted and observed export volume for small floods at the Glen Drive culvert is considered a residual for processes unaccounted for in the wood budget or errors from extrapolating limited data, similar to sediment budgets (e.g. Kondolf and Matthews 1991). This residual is added to the predicted export volumes to the FDS basin for both small and large floods.

Table 1.
Physical characteristics of the study reaches.

Reach No.	Length (m)	Bankfull width (m)	Channel area (ha)	Drainage area (km^2)	Channel slope (%)
1 Fairfax	295	6.7	0.20	4.1	0.7
2 Baywood	525	6.5	0.34	1.75	1.0
3 U. Fairfax	279	6.5	0.18	1.98	1.8

Conversion factors: 1 m = 3.28 ft, 1 ha = 2.47 acres , 1 km^2 = 0.386 mi^2

Wood Recruitment and Storage in Study Reaches. To parameterize wood recruitment rates and storage, we surveyed 1.1 km of channel from the FDS basin to areas upstream of several culverts on Baywood Canyon Creek and Upper Fairfax Creek (Figure 2). Table 1 summarizes the physical characteristics of the study reaches. To use our field time efficiently, it was necessary to define a minimum wood piece size for measurement. We surveyed all pieces of wood within the bankfull channel that were ≥ 10 cm (3.9 in) in diameter (as measured in the middle of the log) and 1.5 m (4.9 ft) in length, a size used to define large wood debris throughout the literature since the late 1970s (Ruiz-Villanueva 2016). Wood volumes are calculated as a cylinder. To account for wood volumes less than this size (i.e. branches and twigs) in the wood budget, we multiply the large wood volumes by 1.26 based on the volume ratio of branches less than 10 cm (3.9 in) diameter to trunk (stem or bole) for hardwoods (MacFarlane 2010, Ver Planck and MacFarlane 2014). We also measured bankfull channel width approximately every 150 m (164 yd). Channel distance and bankfull width were measured with a range finder and tape, respectively.

Table 2.

Large wood characteristics of the study reaches: mean age, recruitment rates, storage, jams. Volumes are for solid wood; fine wood debris volume is not included.

Reach No.	Mean age (yrs) recruit LW[a]				LW recruitment rates $m^3\ ha^{-1}\ yr^{-1}$				All LW				Jams	
	Erosion	Mortality	Landslide	All	Erosion	Mortality	Landslide	All	no. pieces	storage $m^3\ ha^{-1}$	ave diam (m)	ave length (m)	no. jams	prop blocked[c]
1 Fairfax	14.5	--	--	14.5	1.6	--	--	1.6	17	28.4	0.24	3.9	1	0.3
2 Boxwood	11.0	9.5	11.2	10.6	1.9	0.6	0.3	2.7	44	39.5	0.23	5.7	9	0.47
3 U. Fairfax	18.0	--	4.4	12.6	0.5	--	0.5	1.0	19	22.6	0.19	3.7	3	0.65

Notes

a Large Wood (>10 cm diameter,1.5 m length)

b average proportion of bankfull channel width blocked by jams

Conversion factors: 1 m = 3.28 ft, 1 $m^3\ ha^{-1}$ = 0.53 $yd^3\ acre^{-1}$.

Recruitment rates (W_r) were calculated by estimating the age of recruited pieces: recruited live wood was dated by cutting vertical limbs that grew after the piece fell into the channel and counting annual growth rings; recruited dead wood was aged using decay classes for hardwoods and associated age. The recruitment rate is calculated as the total volume of recruited wood divided by the mean age of all recruited wood (Benda et al. 2002, Benda and Sias 2003, Benda and Bigelow 2014). Wood storage volume (W_s) includes all recruited wood and all other wood in the channel.

We measured 114 pieces of wood over 1.1 km (0.68 mi) of channel in the Fairfax Creek watershed (Figure 2). Calculated storage volumes and recruitment rates (Table 2) are generally an order of magnitude lower than literature values for Northern California streams (Benda and Bigelow 2014). Bank erosion was the dominant wood recruitment process (Table 2). Live wood rooted to channel banks comprised 56% of the total wood storage, the remaining comprised of dead wood (44%). These surveyed wood storage volumes and recruitment rates were not sufficient to produce the observed 230 m^3 (300 yd^3) wood exported in the 2012 small flood (Q_3). The surveyed reaches are in a residential area, and there was evidence of substantial wood removal from channels (cut logs in the channel, cut wood piles on channel banks), presumably by residents trying to prevent flooding and bank erosion from wood jams. The channel network above the study reaches are primarily in open space parkland free of contemporary wood removal activities. In addition, the steeper upland reaches bound by hillslopes likely have higher recruitment of wood from streamside slides, which can be a substantial wood recruitment process in the Coast Ranges (Benda et al. 2002, Benda and Bigelow 2014). Consequently, we apply the wood storage values to the study reaches only and use a proxy storage value for the upland watershed (see below). For all channels in the watershed, we developed a recruitment rate (W_r) back-calculated from the observed 230 m^3 (300 yd^3) wood export volume for Fairfax Creek using equation 1, where the export volume is divided by the Fairfax Creek watershed channel area (4.19 ha [10.4 acres]) , and further divided by 3 since it was 3-year event. The back-calculated recruitment rate of 14 $m^3\ ha^{-1}$ (7.4 $yd^3\ acre^{-1}$) is within the range of values reported for Northern California streams (Benda and Bigelow 2014).

Proxy Wood Storage for Upland Watershed. As a proxy for less impacted wood storage (W_s) in the upland watershed, we use large wood storage values published for San Geronimo Creek (Lawrence et al. 2013), a watershed adjacent to Fairfax Creek with similar riparian hardwoods. To account for fine wood debris (i.e. branches and twigs), we multiply the San Geronimo large wood volumes by 1.26 based on the volume ratio of branches less than 10 cm diameter to trunk (stem or bole) for hardwoods (MacFarlane 2010, Ver Planck and MacFarlane 2014).

Large Flood Wood Recruitment from Bank Erosion. A large flood wood recruitment rate from bank erosion was calculated from data collected from the study reaches. We have no way of constraining where the threshold for substantial erosion and mobility of live trees from the channel begins, but it was crossed in the 2005 flood (Q_{100}). Consequently, we calculated the wood recruitment rate from bank erosion during large floods using all trees recruited from bank erosion that dated to near the 2005 flood (Q_{100}). Because wood is actively removed from the study reaches, this rate is underestimated.

Large Flood Plain Wood Recruitment. To estimate flood plain or hillslope wood captured in large floods, we first estimated the Q_{100} flood plain area based on the difference between bankfull (Q_{BF}) and Q_{100} flood widths derived from channel cross sections and modelled water surface elevations (data from Stetson Engineers 2018). On average, the Q_{100} widths were 2.2 times larger than Q_{BF} widths, so flood plain area was estimated as 1.2 times bankfull channel area. The average Q_{100} water depth above the flood plain averaged 0.72 m (2.4 feet), sufficient to enhance mobility for diameters of wood in the study reach (i.e. ratio of piece diameter to flow depth ≥ 1, Haga et al. 2002), and consequently floodp lain wood is likely recruited rather than deposited. In addition, Q_{100} flows are confined by the incised channel walls, promoting recruitment rather than deposition of flood plain wood. Since we did not measure flood plain wood in our surveys, the volume of flood plain wood in each channel segment was estimated based on flood plain dead wood storage values for San Geronimo Creek (Lawrence et al. 2013).

6.2.3 Wood Export Predictions

Stream Network. To calculate wood export (W_o), we created a synthetic stream network for the basin derived from a 2m DEM. Algorithms for flow direction and channel delineation are described in Miller (2003), Clarke et al. (2008), and Miller et al. (2015). The D-infinity algorithm (Tarboton 1997) was used to calculate flow accumulation values and identify channel initiation points. The channel network was divided into a linked set of channel segments, where individual channel reach lengths averaged 112 m (122 yd) (range 78 - 157 m [85 - 172 yd]) . Contributing area and channel length were calculated from the DEM for each segment. Regional regressions for Marin and Sonoma Counties (Collins and Leventhal 2013) were used to estimate bankfull channel width for each channel segment based on drainage area and adjusted to meet our field observations of bankfull width. The channel area of each segment was calculated as the product of channel length and adjusted bankfull width. Wood recruitment and storage values were applied (extrapolated) to the entire channel network based on channel area.

Wood Mobility. Mobile pieces available for wood export were defined based on the ratio of piece length to bankfull channel width (P_L/C_W) or downstream culvert width (see Figure 2), whichever was smaller. The piece length to culvert width factor was used to predict accumulation volumes at culverts and accordingly reduce the volume exported downstream. Many studies in the Pacific Northwest suggest that pieces less than bankfull width are mobile (Bilby 1984, Lienkaemper and Swanson 1987), while others have defined mobile pieces up to twice bankfull width for hardwood forests with smaller diameter wood, similar to the Fairfax Creek watershed (Benda et al. 2018). Consequently, we used a P_L/C_W mobility factor of 2, meaning that pieces with lengths twice bankfull width and shorter are mobile during flood flows.

To determine the proportion of mobile wood volume in each channel segment, we use a regression relationship between the surveyed wood volumes (cumulative distribution) and piece lengths for dead and live wood (including fine wood debris, see earlier) (Figure 4), multiplied by the mobility factor of 2. The cumulative distribution shows live wood pieces are generally longer than dead wood pieces, reflecting that living wood is more stable and remains in place much longer than dead wood (e.g. Opperman and Merenlender 2007), until eroded and killed in large floods, while dead wood breaks down from mechanical abrasion during transport downstream.

Studies that track wood movement find that, once mobilized, the distance a piece is transported downstream is extremely variable and dependent on myriad factors, including piece characteristics, channel characteristics, and the flood hydrograph (Kramer and Wohl 2017), all factors we cannot account for in this brief study. Consequently, we use a simplifying assumption that once mobilized, wood pieces travel to the outlet.

Loose Wood Factor. The predicted wood export volumes are multiplied by 1.3 to account for the 30% void space in loose wood piles (e.g. bulk storage, Steeb et al. 2016). This allows a comparison to the observed wood export volume at the Glen Drive culvert, and an estimate of the bulk volumes that may have to be removed from the FDS basin.

6.3 Results and Discussion

6.3.1 General Observations

To determine which wood piece sizes (diameters and lengths) could lodge on the basin weir or diversion structure crest and spillway requires hydraulic evaluation or modeling (e.g.

Gschnitzer et al. 2017, Schalko et al. 2019). Wood pieces with large diameters and long lengths have a higher potential to lodge at structures than small pieces. Once a large "key" piece or pieces lodge, smaller pieces can accumulate behind it, forming a jam. Since all piece sizes are of potential concern, we characterize the size of all large wood in the survey reaches (see later). Wood pieces lodging on the gated culvert may be less likely since the partial opening is under water during flood operation. Similarly, impact damage to the basin weir or diversion structure from large logs may have a low probability, as the backwater from the diversion slows the velocity of floating logs. Backwater from the FDS operation during Q_{100} flows extends roughly 320 m (350 yd) upstream, with water depths on the order of 3.2 m (10.5 feet) near the diversion structure. We did not evaluate these backwater effects on wood transport, but presumably mobility and transport are enhanced, similar to a stream wood entering a reservoir, creating mobile rafts of wood.

The 230 m^3 (300 yd^3) wood exported by a Q_3 flood is the most useful empirical observation from the Fairfax Creek watershed. This wood volume from a small flood could potentially lodge on the FDS basin basin weir or spillway crests. Large floods should produce higher quantities of wood and can include whole living trees eroded from the channel or recruited from the riparian stand by bank erosion. As mentioned earlier, we do not have the observations to constrain the threshold where bank erosion of live in channel wood and from riparian stands begin, but there is presumably a linear or power relationship between bank erosion versus both flood size and drainage area (e.g. Benda et al. 2018). So, a few live trees erode and move in small floods and many trees in large floods. The oldest recruited trees in Fairfax Creek date roughly back to the 2005 flood (Q_{100}), indicating that all the previous recruited live wood was scoured by bank erosion and transported in this event, and substantial amounts of new live wood were recruited to the channel by bank erosion.

6.3.2 Large Wood Characteristics

A longitudinal profile of wood storage along the study reaches (Figure 5) shows large spatial variation, where high wood storage is concentrated at recent recruitment from localized bank erosion often creating wood jams, followed by long stretches devoid of wood, in part affected by removal of wood by residents. The frequency distribution of measured large wood piece diameters and piece lengths (Figure 6) shows a right skewed distribution, where there are many small pieces and fewer large pieces, reflecting both da Vinci's rule for tree branching ("all the branches of a tree at every stage of its height when put together are equal in thickness to the trunk") and the gradual breakdown of whole trees recruited to the channel. This distribution is often reflected in wood jams, where larger "key" pieces create jams by blocking the channel and accumulating smaller pieces (Figure 7).

This scenario of jam formation in channels is similar to potential jam formation at the FDS diversion structures, where one of the *few* large wood pieces may lodge on the diversion infrastructure with *many* small pieces accumulating behind it, forming a jam.

6.3.3 Wood Export

Table 3 summarizes the parameters used to predict wood export and the resulting volume predictions for small and large floods, predicted small and large flood export volumes at the Sunnyside FDS basin are 182 and 352 m^3 (238 and 460 yd^3) respectively, or roughly 23 to 46 dump truck loads of wood. These estimated wood export volumes are within the range of wood exported by floods from basins of similar size compiled in two recent review papers covering wood export (Comiti et al. 2016, Ruiz-Villanueva et al. 2017, Figure 8).

Table 3.

Parameters used to estimate wood export and predicted wood export volumes.

Small Flood Parameter/Prediction	**Applied to**	**Values**	**Units**
Fairfax dead wood storage (measured)	study reaches	28	m^3 ha^{-1}
San Geronimo dead wood storage (proxy)	upper reaches	63	m^3 ha^{-1}
Fairfax recruit wood (back calculated)	all reaches	14	m^3 ha^{-1}
mobility factor: piece length/channel width	all reaches	2	
porosity factor: solid wood to loose wood	predicted export volumes	1.3	
Export observed at Glen Dr culvert (DA 4.8 km^2)		230	m^3
Export predicted at Glen Dr culvert (DA 4.8 km^2)		186	m^3
Deposition predicted behind upstream culverts		39	m^3
Observed and predicted difference (residual)		20	%
Export predicted at FDS Basin (DA 4.1 km^2)		**182**	**m^3**
Deposition predicted behind upstream culverts		31	m^3
Large Flood Parameter/Prediction			
Fairfax dead wood storage (measured)	study reaches	28	m^3 ha^{-1}
Fairfax live wood storage (measured)	study reaches	36	m^3 ha^{-1}
San Geronimo dead wood storage (proxy)	upper reaches	63	m^3 ha^{-1}
San Geronimo live wood storage (proxy)	upper reaches	50	m^3 ha^{-1}
San Geronimo flood plain wood storage (proxy)	all reaches	13	m^3 ha^{-1}
Fairfax recruit wood (back calculated)	all reaches	14	m^3 ha^{-1}
Fairfax large flood bank erosion recruit wood	all reaches	23	m^3 ha^{-1}
mobility factor: piece length/channel width	all reaches	2	
porosity factor: solid wood to loose wood	predicted export volumes	1.3	
Export predicted at FDS Basin (DA 4.1 km^2)		**352**	**m^3**
Deposition predicted behind upstream culverts		65	m^3

Conversion factors: 1 m^3 = 1.31 yd^3, 1 m^3 ha^{-1} = 0.53 yd^3 $acre^{-1}$

Figure 9 shows the predicted percentage of all mobile wood predicted for a large flood from the Fairfax Creek watershed, where the majority of mobile wood is supplied from the larger 3rd and 4th order channels. Any debris removal or reduction efforts (described later) should be focused on these reaches.

6.3.4 Primary Implications of the Wood Budget for the FDS Basin

In summary, the wood budget constructed for the Fairfax Creek watershed provides several critical pieces of data to more effectively plan for and manage wood transported to the FDS basin in small and large floods:

1) **Wood supply processes and implications**: Live wood rooted to channel banks comprises 56% of the wood stored in the channel of Fairfax Creek, and most of the wood enters the channel from bank erosion (Table 2), in part because the channel has incised and is currently in the widening phase of "incised channel evolution" (see Schumm et al. 1984, Schumm 1999). Most wood recruited to the channel by bank erosion remains alive because it is still rooted to the bank (e.g., Opperman and Merenlender 2007). The oldest recruited trees in the channel date back to the 2005 flood (Q_{100}), indicating that all previous live and dead in-channel wood was eroded from the channel banks and bed in this remarkable event. Because wood recruited in large floods include both whole living trees eroded from the channel and the riparian trees on the adjacent flood plain and terrace (former flood plain prior to incision), these pieces with rootwads are likely to impact and hang on the FDS structures, allowing smaller pieces to accumulate behind them, creating a jam that could cause failure of the FDS basin. The dominance of wood recruitment by bank erosion in Fairfax Creek and the evidence of massive bank erosion and scouring of channel wood during the 2005 flood indicate that countermeasures are necessary to prevent failure of the FDS structures.

2) **Wood export volumes**: The wood export estimates for small (on the scale of Q_3) and large (multi-decade to Q_{100}) floods provide an order of magnitude estimate of wood volumes the District should initially plan for at the FDS basin. For example, should the District initially plan to annually manage 10, 100, 1,000, or 10,000 m^3 of wood exported to the FDS basin? Also, how much wood could be exported from episodic large floods and could it cause failure of the FDS structures? Based on the wood budget calibrated to one empirical wood export observation, estimated wood exported for small and large floods are on the order of 182 and 352 m^3 (238 and 460 yd^3), respectively, or more broadly in order of magnitude estimates, 100 - 900 m^3 (130 - 1,200 yd^3). These estimated wood export volumes are within the range of wood exported by floods from basins of similar size compiled in two recent review papers on wood export (Comiti et al. 2016, Ruiz-Villanueva et al. 2017, Figure 8). These estimated wood volumes also indicate that countermeasures are necessary to prevent failure of the FDS structures. After construction of the FDS basin, the District can use empirical observations of wood volumes to adjust their future maintenance costs more accurately.

3) **Dominant Wood Source Area to FDS Basin**: The wood budget identifies the primary source areas of wood exported to the FDS Basin based on wood storage volumes, wood piece lengths, and wood transport (wood mobility: wood piece length/channel width ratio). Figure 9 shows the predicted percentage of all mobile wood predicted for a large flood from the Fairfax Creek watershed, where the majority of mobile wood is supplied from the larger 3rd and 4th order channels (shown in red and orange). Any debris removal or reduction efforts allowed by regulatory agencies should be focused on these reaches.

6.4 Options for Additional Study

The estimates of wood export from small and large floods from Fairfax Creek are an approximation but likely correspond to the correct order of magnitude in the context of a wood budgeting techniques, similar to estimates from sediment budgets (e.g. Reid and Dunne 1996). If better estimates of wood export are desired by the District, additional field work and more detailed modeling options are outlined below. However, the observed 230 m^3 exported wood volume from a Q_3 flood event alone suggests that efforts to mitigate wood debris impacts to FDS basin infrastructure are warranted. Efforts to improve wood export estimates could include stream surveys in the upland reaches to provide reliable estimates of wood storage and recruitment rates. Steeper channels bound by hillslopes likely have a high contribution of wood from streamside slides and are free of wood removal impacts. The surveys could include some subsampling of fine wood debris and overbank/flood plain wood. Better estimates of wood transport and export can be developed by tagging and tracking wood pieces (e.g. Ravazzolo et al. 2015) and video monitoring (e.g. Senter et al. 2017), respectively. More detailed estimates of wood mobility and export based on flow depth/wood diameter and flood width/piece length are possible with approaches that include simple to complex flow modeling (e.g. Mazzorana et al. 2011, Benda et al. 2018). Perhaps the cheapest, simplest, and most useful effort to improve estimates of wood export could involve the District soliciting observations of wood accumulations behind bridges and culverts from known flood events throughout Marin County (e.g. from Public Works agencies). If sufficient observations were available, wood export volumes versus discharge and drainage area curves (e.g., Figure 8) could be developed for Marin County watersheds and applied to management of the Sunnyside FDS basin on Fairfax Creek and any similar projects.

A wood debris retention structure may be incorporated in the FDS basin facility for mitigating the residual risk of standing live trees in the management reach that are outside the scope of the recommend piece size reduction monitoring and maintenance program from being entrained into Fairfax Creek by rare-event bank erosion and floated into the basin where they would potentially be "key" pieces for a jam formation on the basin weir or spillway crest. The absolute number of live standing trees that may enter Fairfax Creek and Baywood Canyon Creek by rare-event bank erosion within the 1,500-foot-long management reach may not be large enough to justify the capital and recurring operations and maintenance costs of a retention structure. Rather, the plan recommends evaluating rare-event bank erosion susceptibility within the management reach in more detail and first considering the potential for targeted bank erosion protection measures, and adding bank erosion monitoring to the annual and post-flood monitoring and maintenance program measures to substantially reduce the residual risk of during-flood live tree recruitment.

Acknowledgements

Matt Smeltzer and Paul Bigelow conducted field work and prepared the report. Dr. Lee Benda assisted in report writing and developing the wood budget approach to estimate wood export. Kevin Andras created the attributed stream layer.

References

Benda, L.E., Bigelow, P., Worsley, T.M., 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32, 1460–1477.

Benda, L., and J. Sias. 2003. A quantitative frame work for evaluating the wood budget. Forest Ecology and Management 172:1-16.

Benda, L. and Bigelow, P., 2014. On the patterns and processes of wood in northern California streams. *Geomorphology*, *209*, pp.79-97.

Benda, L., D.J. Miller, K. Andras, P. Bigelow, 2018. Analysis of wood debris sources, transport and export volumes in the Susquehanna River basin. Consulting report prepared for WSP and Exelon by TerrainWorks. 44 pp.

Bigelow, P., Benda, L. and Pearce, S., 2016. Delineating incised stream sediment sources within a San Francisco Bay tributary basin. *Earth Surface Dynamics*, *4*(3).

Bilby, R. E. 1984. Removal of wood debris may affect stream channel stability. J. For. 82: 609-613.

Bradley, J.B., Richards, D.L. and Bahner, C.C., 2005. *Debris control structures: Evaluation and countermeasures*. US Department of Transportation, Federal Highway Administration.

Braudrick, C. A., and G. E. Grant. 2000. When do logs move in rivers? Water Resources Research 36:571-583.

Clarke, S.E., Burnett, K.M. and Miller, D.J., 2008. Modeling streams and hydrogeomorphic attributes in Oregon from digital and field data 1. *JAWRA Journal of the American Water Resources Association*, *44*(2), pp.459-477.

Collins, L. and Leventhal, R., 2013. Regional curves of hydraulic geometry for wadeable streams in Marin and Sonoma Counties, San Francisco Bay Area data summary report. May 10, 45 pp.

Comiti, F., Lucía, A. and Rickenmann, D., 2016. Large wood recruitment and transport during large floods: a review. *Geomorphology*, *269*, pp.23-39.

Curran, J.C., 2010. Mobility of large wood debris (LWD) jams in a low gradient channel. *Geomorphology*, *116*(3-4), pp.320-329.

Ellen, S.D., Mark, R.K., Wieczorek, G.F., Wentworth, C.M., Ramsey, D.W. and May, T.E., 1997. *Map showing principal debris-flow source areas in the San Francisco Bay region, California* (No. 97-745-E). US Dept. of the Interior, US Geological Survey.

Fremier, A.K., Seo, J.I., Nakamura, F., 2010. Watershed controls on the export of large wood from stream corridors. Geomorphology 117, 33–43.

Graymer, R.W., B.C. Moring, G.J. Saucedo, C.M. Wentworth, E.E. Brabb, and K.L. Knudsen. 2006. Geologic Map of the San Francisco Bay Region. USGS Scientific Investigations Map 2918. 1:275,000.

Gschnitzer, T., Gems, B., Mazzorana, B. and Aufleger, M., 2017. Towards a robust assessment of bridge clogging processes in flood risk management. *Geomorphology*, *279*, pp.128-140.

Haga, H., Kumagai, T.O., Otsuki, K. and Ogawa, S., 2002. Transport and retention of coarse wood debris in mountain streams: An *in situ* field experiment of log transport and a field survey of coarse wood debris distribution. *Water Resources Research*, *38*(8), pp.1-16.

Iroumé, A., Mao, L., Andreoli, A., Ulloa, H., Paz Ardiles, M., 2015. Large wood mobility processes in low-order Chilean river channels. Geomorphology 228, 681–693. http://dx.doi.org/10.1016/j.geomorph.2014.10.025.

Kondolf, G.M. and Matthews, W.G., 1991. Unmeasured residuals in sediment budgets: a cautionary note. *Water Resources Research*, *27*(9), pp.2483-2486.

Kramer, N. and Wohl, E., 2017. Rules of the road: A qualitative and quantitative synthesis of large wood transport through drainage networks. *Geomorphology*, *279*, pp.74-97.

Lawrence, J.E., Resh, V.H. and Cover, M.R., 2013. Large-wood loading from natural and engineered processes at the watershed scale. *River Research and Applications*, *29*(8), pp.1030-1041.

Lienkaemper, G.W. and Swanson, F.J., 1987. Dynamics of large wood debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research*, *17*(2), pp.150-156.

Lockaby, M. 2019. Personal e-mail communication from Mark Lockaby (Town of Fairfax Public Works Manager) to Hugh Davis (Marin County Flood Control District). August 10.

MacFarlane, D.W., 2010. Predicting branch to bole volume scaling relationships from varying centroids of tree bole volume. *Canadian journal of forest research*, *40*(12), pp.2278-2289.

Mazzorana, B., Hübl, J., Zischg, A. and Largiader, A., 2011. Modelling wood material transport and deposition in alpine rivers. *Natural Hazards*, *56*(2), pp.425-449.

Mazzorana, B., Ruiz-Villanueva, V., Marchi, L., Cavalli, M., Gems, B., Gschnitzer, T., Mao, L., Iroumé, A. and Valdebenito, G., 2018. Assessing and mitigating large wood-related hazards in mountain streams: recent approaches. *Journal of Flood Risk Management*, *11*(2), pp.207-222.

Miller, D.J., 2003. Programs for DEM Analysis, Landscape Dynamics and Forest Management. General Technical Report RMRS-GTR-101CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 33 pp.

Miller, D., 2015. Creation of a Digital Flowline Network from IfSAR 5-m DEMs for the Matanuska-Susitna Basins: A Resource for NHD Updates in Alaska. Consultant report to The Nature Conservancy. Anchorage, Alaska, 33 pp.

Moulin, B. and Piégay, H., 2004. Characteristics and temporal variability of large wood debris trapped in a reservoir on the River Rhone (Rhone): implications for river basin management. *River Research and Applications*, *20*(1), pp.79-97.

Nakamura, F., and F.J. Swanson. 1993. Effects of coarse wood debris on morphology and sediment storage of a mountain stream in western Oregon. Earth Surface Processes and Landforms 18:43-61.

Opperman, J.J. and Merenlender, A.M., 2007. Living trees provide stable large wood in streams. *Earth Surface Processes and Landforms*, *32*(8), pp.1229-1238.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created August 2019.

Ravazzolo, D., Mao, L., Picco, L. and Lenzi, M.A., 2015. Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. *Geomorphology*, *228*, pp.226-233.

Reid, L.M. and Dunne, T. 1996. Rapid evaluation of Sediment Budgets. Germany: GeoEcology paperbacks, Catena Verlag.

Ruiz-Villanueva, V., Piégay, H., Gurnell, A.M., Marston, R.A. and Stoffel, M., 2016. Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. *Reviews of Geophysics*, *54*(3), pp.611-652.

Schalko, I., Schmocker, L., Weitbrecht, V. and Boes, R.M., 2019. Laboratory study on wood accumulation probability at bridge piers. *Journal of Hydraulic Research*, pp.1-16.

Schumm, S.A., Harvey, M.D. and Watson, C.C., 1984. *Incised channels: morphology, dynamics, and control*. Water Resources Publications.

Schumm, S.A., 1999. Causes and controls of channel incision, in: Incised river channels: processes, forms, engineering and management, edited by: Darby, S. E. and Simon, A., John Wiley and Sons: London, pp. 19–33.

Senter, A., Pasternack, G., Piégay, H. and Vaughan, M., 2017. Wood export prediction at the watershed scale. *Earth Surface Processes and Landforms*, *42*(14), pp.2377-2392.

Stetson Engineers and geomorphDESIGN, 2009. Technical memorandum no. 1: existing conditions analysis for Corte Madera Creek. 18 pp.

Stetson Engineers, 2018. Report on hydraulic analysis of San Anselmo flood risk reduction project, option 2a with revised Sunnyside detention basin and complete removal of building bridge #2. January 29.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water resources research*, *33*(2), pp.309-319.

Ver Planck, N.R. and MacFarlane, D.W., 2014. Modelling vertical allocation of tree stem and branch volume for hardwoods. *Forestry: An International Journal of Forest Research*, *87*(3), pp.459-469.

Welber, M., Bertoldi, W., Tubino, M., 2013. Wood dispersal in braided streams: results from physical modeling. Water Resour. Res. 49, 7388–7400.

Wentworth, C.M., Graham, S.E., Pike, R.J., Beukelman, G.S., Ramsey, D.W. and Barron, A.D., 1997. *Summary distribution of slides and earth flows in the San Francisco Bay Region, California* (No. 97-745-C). US Dept. of the Interior, US Geological Survey.

Appendix A

Large dead wood lengths, diameters, and volumes within the bankfull channel from the FDS basin upstream to first culvert on Baywood Canyon Creek (Figure 2). Note that some bay laurel pieces at the same distance (e.g. three x 0.3 diameter pieces at 250 m) are actually one piece joined at the rootwad, but the stem volumes were calculated as individual pieces, see photo below.

Dead bay laurel 250 m (273 yd) upstream from FDS basin.

Appendix A - Dead Wood

Reach	**Distance moving US**		**Diameter**		**Length**		**Volume**		**Jam**
	(m)	**(yd)**	**(m)**	**(ft)**	**(m)**	**(ft)**	**(m^3)**	**(yd^3)**	
1 Fairfax	21	23	0.2	0.7	3	9.8	0.09	0.12	
1 Fairfax	90	98	0.2	0.7	1.5	4.9	0.05	0.06	
1 Fairfax	105	115	0.1	0.3	4	13	0.03	0.04	
1 Fairfax	145	159	0.15	0.5	4	13	0.07	0.09	
1 Fairfax	165	180	0.2	0.7	6	20	0.19	0.25	
1 Fairfax	165	180	0.15	0.5	4	13	0.07	0.09	
1 Fairfax	200	219	0.2	0.7	1.5	4.9	0.05	0.06	
1 Fairfax	217	237	0.4	1.3	1.5	4.9	0.19	0.25	
1 Fairfax	250	273	0.3	1.0	6	20	0.42	0.55	Y
1 Fairfax	250	273	0.3	1.0	6	20	0.42	0.55	Y
1 Fairfax	250	273	0.3	1.0	6	20	0.42	0.55	Y
1 Fairfax	250	273	0.2	0.7	3	9.8	0.09	0.12	Y
1 Fairfax	250	273	0.25	0.8	2	6.6	0.10	0.13	Y
1 Fairfax	266	291	0.1	0.3	2	6.6	0.02	0.02	
1 Fairfax	268	293	0.3	1.0	1.5	4.9	0.11	0.14	
1 Fairfax	295	323	0.4	1.3	2.5	8.2	0.31	0.41	
2 Baywood	320	350	0.2	0.7	1.5	4.9	0.05	0.06	Y
2 Baywood	320	350	0.5	1.6	1.5	4.9	0.29	0.39	Y
2 Baywood	350	383	0.2	0.7	10	33	0.31	0.41	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	350	383	0.1	0.3	3	9.8	0.02	0.03	Y
2 Baywood	415	454	0.2	0.7	4	13	0.13	0.16	
2 Baywood	415	454	0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	415	454	0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	415	454	0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	415	454	0.1	0.3	3	9.8	0.02	0.03	
Culvert 3.6 m (12 ft) wide at 471 m (515 yd)									

Appendix B

Piece lengths, diameters, and volumes of all large wood (dead and live) within the bankfull channel in all study reaches.

Note that some bay laurel pieces at the same distance are actually one piece joined at the rootwad, but the stem volumes were calculated as individual pieces, see example from reach #2 on Baywood Canyon Creek below.

Multiple-stem down-dead trees in Baywood Canyon Creek segment of management reach.

Appendix B - All Live and Dead Wood

	Distance (moving US)			Live	Age	Diameter		Length		Volume		
Reach	**(m)**	**(yd)**	**Species**	**Dead**	**(yr)**	**(m)**	**(ft)**	**(m)**	**(ft)**	**(m^3)**	**(yd^3)**	**Jam**
1 Fairfax	3	3	willow	live	5	0.2	0.7	3	9.8	0.09	0.12	
1 Fairfax	21	23		dead		0.2	0.7	3	9.8	0.09	0.12	Y
1 Fairfax	90	98		dead		0.2	0.7	1.5	4.9	0.05	0.06	
1 Fairfax	105	115		dead		0.1	0.3	4	13	0.03	0.04	Y
1 Fairfax	145	159		dead		0.15	0.5	4	13	0.07	0.09	Y
1 Fairfax	165	180		dead		0.2	0.7	6	20	0.19	0.25	Y
1 Fairfax	165	180		dead		0.15	0.5	4	13	0.07	0.09	Y
1 Fairfax	200	219		dead		0.2	0.7	1.5	4.9	0.05	0.06	
1 Fairfax	200	219	willow	live	17.5	0.3	1.0	6	20	0.42	0.55	
1 Fairfax	217	237		dead		0.4	1.3	1.5	4.9	0.19	0.25	
1 Fairfax	250	273		dead		0.2	0.7	3	9.8	0.09	0.12	Y
1 Fairfax	250	273		dead		0.25	0.8	2	6.6	0.10	0.13	Y
1 Fairfax	250	273		dead		0.3	1.0	14	46	0.99	1.29	Y
1 Fairfax	250	273		dead		0.3	1.0	14	46	0.99	1.29	Y
1 Fairfax	250	273		dead		0.3	1.0	14	46	0.99	1.29	Y
1 Fairfax	266	291		dead		0.1	0.3	2	6.6	0.02	0.02	
1 Fairfax	268	293		dead		0.3	1.0	1.5	4.9	0.11	0.14	
1 Fairfax	295	323		dead		0.4	1.3	2.5	8.2	0.31	0.41	
1 Fairfax	295	323	bay	live	14	0.4	1.3	6	20	0.75	0.99	
2 Baywood	305	334	bay	live	5	0.25	0.8	11	36	0.54	0.71	
2 Baywood	320	350		dead		0.2	0.7	1.5	4.9	0.05	0.06	Y
2 Baywood	320	350		dead		0.5	1.6	1.5	4.9	0.29	0.39	Y
2 Baywood	320	350	bay	live	20	0.3	1.0	12	39	0.85	1.11	
2 Baywood	350	383		dead		0.2	0.7	10	33	0.31	0.41	Y
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	350	383		dead		0.1	0.3	3	9.8	0.02	0.03	
2 Baywood	375	410	bay	live	2	0.25	0.8	12	39	0.59	0.77	
2 Baywood	415	454		dead		0.2	0.7	4	13	0.13	0.16	
2 Baywood	415	454		dead		0.1	0.3	3	10	0.02	0.03	Y

	Distance (moving US)			Live	Age	Diameter		Length		Volume		
Reach	**(m)**	**(yd)**	**Species**	**Dead**	**(yr)**	**(m)**	**(ft)**	**(m)**	**(ft)**	**(m^3)**	**(yd^3)**	**Jam**
2 Baywood	415	454		dead		0.1	0.3	3	10	0.02	0.03	Y
2 Baywood	415	454		dead		0.1	0.3	3	10	0.02	0.03	Y
2 Baywood	415	454		dead		0.1	0.3	3	10	0.02	0.03	Y
2 Baywood	425	465	bay	live	3.5	0.2	0.7	12	39	0.38	0.49	Y
2 Baywood	425	465	bay	live	3.5	0.2	0.7	12	39	0.38	0.49	Y
2 Baywood	471	515	**Culvert 3.6 m (12 ft) wide**									
2 Baywood	512	560	bay	live	17.5	0.5	1.6	2	6.6	0.39	0.51	
2 Baywood	520	569		dead		0.4	1.3	2.5	8.2	0.31	0.41	Y
2 Baywood	520	569		dead		0.2	0.7	3	9.8	0.09	0.12	Y
2 Baywood	520	569		dead		0.2	0.7	1.5	4.9	0.05	0.06	Y
2 Baywood	535	585	bay	live	17.5	0.4	1.3	1.5	4.9	0.19	0.25	
2 Baywood	535	585		dead		0.2	0.7	1.5	4.9	0.05	0.06	
2 Baywood	535	585		dead		0.2	0.7	1.5	4.9	0.05	0.06	
2 Baywood	538	588		dead		0.1	0.3	1.5	4.9	0.01	0.02	Y
2 Baywood	538	588	bay	live	17.5	0.4	1.3	2	6.6	0.25	0.33	
2 Baywood	558	610		dead		0.1	0.3	4	13	0.03	0.04	
2 Baywood	580	634		dead		0.15	0.5	5	16	0.09	0.12	Y
2 Baywood	580	634		dead		0.2	0.7	3	9.8	0.09	0.12	Y
2 Baywood	580	634	eldberry	live	4.5	0.2	0.7	8	26	0.25	0.33	
2 Baywood	590	645	willow	live	14	0.2	0.7	12	39	0.38	0.49	
2 Baywood	600	656		dead		0.3	1.0	8	26	0.57	0.74	Y
2 Baywood	600	656	willow	live	22.5	0.35	1.1	12	39	1.15	1.51	
2 Baywood	620	678		dead		0.25	0.8	7	23	0.34	0.45	
2 Baywood	650	711		dead		0.15	0.5	4.5	15	0.08	0.10	
2 Baywood	675	738		dead		0.1	0.3	2	6.6	0.02	0.02	
2 Baywood	675	738		dead		0.25	0.8	2	6.6	0.10	0.13	
2 Baywood	685	749		dead		0.2	0.7	2.5	8.2	0.08	0.10	
2 Baywood	695	760		dead		0.1	0.3	2	6.6	0.02	0.02	Y
2 Baywood	695	760		dead		0.1	0.3	2	6.6	0.02	0.02	Y
2 Baywood	715	782		dead		0.2	0.7	2	6.6	0.06	0.08	
2 Baywood	735	804		dead		0.4	1.3	8	26	1.01	1.31	Y
2 Baywood	740	809		dead		0.4	1.3	8	26	1.01	1.31	Y
2 Baywood	740	809		dead		0.5	1.6	5	16	0.98	1.28	
2 Baywood	760	831	willow	live	4.5	0.2	0.7	6	20	0.19	0.25	Y
2 Baywood	764	836		dead		0.15	0.5	6	20	0.11	0.14	

	Distance (moving US)			Live	Age	Diameter		Length		Volume		
Reach	**(m)**	**(yd)**	**Species**	**Dead**	**(yr)**	**(m)**	**(ft)**	**(m)**	**(ft)**	**(m^3)**	**(yd^3)**	**Jam**
2 Baywood	774	846		dead		0.1	0.3	1.5	4.9	0.01	0.02	Y
2 Baywood	774	846	willow	live	10	0.2	0.7	7	23	0.22	0.29	
2 Baywood	785	858	willow	live	10	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	785	858	willow	live	10	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	785	858	willow	live	10	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	785	858	willow	live	10	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	790	864	willow	live	20	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	790	864	willow	live	20	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	790	864	willow	live	20	0.15	0.5	7	23	0.12	0.16	Y
2 Baywood	800	875		dead		0.2	0.7	3	9.8	0.09	0.12	Y
2 Baywood	800	875	willow	live	5.5	0.15	0.5	8	26	0.14	0.18	
2 Baywood	800	875	willow	live	5.5	0.2	0.7	8	26	0.25	0.33	Y
2 Baywood	820	897	**End reach at tributary with 4.6 m (15 ft) wide culvert**									
3 U Fairfax	0	0	**Start reach at 1.8 m (6 ft) wide culvert**									
3 U Fairfax	15	16		dead		0.25	0.8	2	6.6	0.10	0.13	
3 U Fairfax	61	67		dead		0.2	0.7	3.5	11	0.11	0.14	
3 U Fairfax	61	67		dead		0.15	0.5	2	6.6	0.04	0.05	
3 U Fairfax	61	67	**Culvert 2.0 m (6.5 ft) wide**									
3 U Fairfax	122	133		dead		0.15	0.5	4	13	0.07	0.09	Y
3 U Fairfax	122	133		dead		0.15	0.5	4	13	0.07	0.09	Y
3 U Fairfax	122	133		dead		0.15	0.5	4	13	0.07	0.09	Y
3 U Fairfax	126	138		dead		0.15	0.5	4	13	0.07	0.09	Y
3 U Fairfax	126	138		dead		0.15	0.5	4	13	0.07	0.09	Y
3 U Fairfax	180	197	willow	live	14	0.15	0.5	8	26	0.14	0.18	Y
3 U Fairfax	180	197	willow	live	14	0.15	0.5	8	26	0.14	0.18	Y
3 U Fairfax	180	197	willow	live	14	0.15	0.5	8	26	0.14	0.18	Y
3 U Fairfax	210	230		dead		0.15	0.5	3	9.8	0.05	0.07	
3 U Fairfax	240	262		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	255	279		dead		0.2	0.7	7	23	0.22	0.29	Y
3 U Fairfax	255	279		dead		0.3	1.0	2	6.6	0.14	0.18	Y
3 U Fairfax	255	279		dead		0.2	0.7	8	26	0.25	0.33	Y
3 U Fairfax	255	279		dead		0.15	0.5	1.5	4.9	0.03	0.03	Y
3 U Fairfax	255	279		dead		0.15	0.5	1.5	4.9	0.03	0.03	Y
3 U Fairfax	255	279		dead		0.15	0.5	1.5	4.9	0.03	0.03	Y
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	

	Distance (moving US)			Live	Age	Diameter		Length		Volume		
Reach	**(m)**	**(yd)**	**Species**	**Dead**	**(yr)**	**(m)**	**(ft)**	**(m)**	**(ft)**	**(m^3)**	**(yd^3)**	**Jam**
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	255	279		dead		0.2	0.7	2	6.6	0.06	0.08	
3 U Fairfax	270	295		dead		0.25	0.8	6	20	0.29	0.39	
3 U Fairfax	270	295		dead		0.15	0.5	1.5	4.9	0.03	0.03	Y
3 U Fairfax	270	295		dead		0.15	0.5	1.5	4.9	0.03	0.03	Y
3 U Fairfax	300	328		dead		0.15	0.5	2	6.6	0.04	0.05	
3 U Fairfax	325	355	willow	live	20	0.2	0.7	3	9.8	0.09	0.12	Y
3 U Fairfax	330	361	willow	live	20	0.25	0.8	6	20	0.29	0.39	Y
3 U Fairfax	330	361	willow	live	20	0.25	0.8	6	20	0.29	0.39	Y
3 U Fairfax	330	361	willow	live	20	0.25	0.8	6	20	0.29	0.39	Y
3 U Fairfax	330	361	willow	live	20	0.25	0.8	6	20	0.29	0.39	Y
3 U Fairfax	330	361		dead		0.25	0.8	2	6.6	0.10	0.13	Y