Review of: An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California (prepared by The Pacific Lumber Company, Scotia, California)

Dr. Leslie M. Reid
USDA Forest Service Pacific Southwest Research Station
Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata CA 95521

Table of Contents

List of Figures

List of Tables

Review of: An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California (prepared by The Pacific Lumber Company, Scotia, California)

Dr. Leslie M. Reid
USDA Forest Service Pacific Southwest Research Station
Redwood Sciences Laboratory, 1700 Bayview Drive, Arcata CA 95521

The report by Pacific Lumber Company (PL 1999) that is here reviewed was prepared in response to the decision by the California Department of Forestry (CDF) that new Timber Harvest Plans (THPs) would not be approved in Freshwater and Elk River watersheds until studies were completed that evaluated the relationship between logging and downstream flood hazard and sedimentation in Freshwater Creek and Elk River. The report concludes that there is no evidence that logging has influenced these impacts, and that the requirement for watershed analysis before THPs are approved is therefore unnecessary. However, examination of the report indicates that much of the information it contains supports the opposite conclusion: that recent logging has contributed to sedimentation and increased flood hazard in the two watersheds. Evidence within the report thus suggests that CDF's decision is well-founded.

The report under review is arranged in five sections. The first section is a cover letter, the next three sections are chapters on rainfall patterns, runoff, and channel form, and the fifth section includes responses from four Pacific Lumber Company consultants. Rather than addressing each technical point that requires discussion, I have focused instead on the major issues presented in each chapter and consultant's response. The conclusions of the review are summarized below, and supporting information for the summary statements is included in the body of the review. If further information is required on specific details of the report, I will be happy to provide a more detailed review. At the end of the review I have briefly outlined the kinds of information that may be useful for inclusion in a watershed assessment to better understand the issues of concern in the Freshwater Creek and Elk River watersheds.

The North Coast Regional Water Quality Control Board asked me to prepare this review because (1) I am an expert in cumulative watershed impacts, hydrology, and geomorphology, (2) I am familiar with issues in the area in question, and (3) results of my earlier work provided a focus for the report under review. The review that I have prepared is based on my own research and on research published by others. This technical review represents my own professional opinion as an expert in cumulative watershed impacts, hydrology, and geomorphology, and the review should not be construed as reflecting an official policy position of the USDA Forest Service. It should also be noted that technical reviews, by their nature, focus on opportunities for improvement of a report's content. Technical reviews are intended to point out errors, omissions, and weaknesses in technical content and reasoning. Given limited time available for preparation of reviews, it is not standard practice—and, indeed, is not possible—to acknowledge the points for which no change would be suggested.

Summary

The reviewed report (PL 1999) attempts to demonstrate that logging conducted over the past decade or so in Freshwater and Elk watersheds has not caused increased flooding in downstream portions of the watersheds. However, most of the report's sections include information that supports

the hypothesis that logging has aggravated flood hazard, produce conclusions that contradict field evidence or recently obtained information, or contain analyses that are insufficient or invalid in their present form:

- Chapter 2 on rainfall patterns does not directly address the fundamental question relevant to the flooding issue: do storms of similar sizes produce floods of similar sizes before and after the recent episode of logging began? Photographs included in Chapter 2, however, suggest that flooding is now generated by smaller rainstorms than in the past. Furthermore, the analysis of storm frequency presented in Chapter 2 is not valid because it is based on the assumption that rain gauge records before 1994 are equivalent to those after 1994 even though the gauge was moved in 1994. Data provided by Chapter 2, if accurate, indicate that this assumption is not valid.
- Examination of the main points presented in Chapter 3 on rainfall interception on runoff shows that strong evidence exists that logging is capable of increasing peakflows, that decreased interception of rainfall after forest cover is removed is one of the potential mechanisms for such changes, and that the effect will persist for more than 10 years. Further, Chapter 4’s conclusion that small storms are even more affected by interception loss than large storms indicates that an additional mechanism for increased peakflow changes must also be considered in future calculations: antecedent soil moisture is likely to be higher in cut areas than in forests at the time some major storms occur, thus further increasing potential peakflow volumes.
- The chapter on sediment and channel data (Chapter 4) attempts to test five premises which, if true, would lead to the conclusion that logging-related sediment has contributed to downstream flooding:

  Premise 1. Logging increases the delivery of sediment to streams: the chapter concludes that this is indeed the case

  Premise 2. This increased sediment delivery cannot be accommodated by the stream’s natural sediment transport capability: the chapter’s argument that the channel type and grain size do not facilitate aggradation is contradicted by observed locations of aggradation, documented measurements of aggradation, and observed grain sizes of the aggrading sediment.

  Premise 3. Aggradation occurs in the areas where flooding is of concern: the chapter’s argument that many of the measured cross sections do not show aggradation is countered by the observation that the only long-term measurements made in stream reaches where increased flooding is reported all show channel infilling of 34 to 42%.

  Premise 4. Such aggradation has a significant effect on the flood carrying or “conveyance” capacity of the stream: the chapter’s argument that scour is sufficient during peak flows to increase channel conveyance to near original levels is countered by noting that sediment in transport in the water column occupies nearly the same volume as sediment at rest on the channel bed. Further, field evidence indicates that little, if any, scour occurs on fine-grained deposits on channel banks, which is where the major portion of the sediment accumulates.

  Premise 5. The increase in flooding caused by the reduced conveyance capacity actually leads to the inundation of homes, roads, and other structures that otherwise would not have been flooded: the chapter calculates the effect using the erroneous assumption that shallow water on a floodplain flows at the same velocity as deep water in a channel. When standard methods are used to calculate flow depth, however, results show that a 41% decrease in channel area (approximately equivalent to that measured by PL (1999) on North Fork Elk River) would cause more than a 3-foot increase in stage for what once was a bankfull flow, thus leading to flooding.

The available evidence thus suggests that each premise is true. Given the logical construct posed by Chapter 4, then, the results support the conclusion that logging-related sediment has contributed to downstream flooding in Freshwater Creek and Elk River.

- The consulting report by Dr. O'Connor—when modified to reflect the actual rate of logging and forest canopy removal in Freshwater watershed—suggests that overbank flooding is 1.35 times as frequent now than before the recent increase in logging rate, thus supporting the conclusion that logging has increased the frequency of flooding along lower Freshwater Creek. His conclusion that aggradation is not likely because sediments are too fine-grained is contradicted by direct field observations (Reid 1999), and, by Dr. O'Connor's argument, the presence of fine-grained aggradation suggests that on-going activities provide the primary source of aggrading sediment.
- The major concerns raised by Mr. Patric's consulting report are allayed by evidence he has provided: the measurements he cites for other vegetation types show lower interception losses than those measured in coastal forests, his measurements from coastal forests in Alaska and those he cites from other coastal forests (Patric 1966) show greater interception loss rates than those estimated for coastal forests in California, and he provides an explanation for why interception losses are high in coastal forests.
- The consulting report by Dr. Rice produces a calculated total logging-related sediment input rate to Elk River that is 10 times lower than that documented by an earlier PL consulting report (PWA 1998) to be derived from road-related sources in North Fork Elk River watershed alone.
- The consulting report by Dr. Pyles indicates that local data are needed before the influence of sedimentation on flood frequency can be assessed. The local data provided by the report indicate that the influence of such sedimentation is significant in the Freshwater and Elk watersheds.

It is important to note that conclusions of two of the consultants' reports were influenced by errors of fact (Freshwater logging rates and North Fork Elk River sediment input rates) that indicate that consultants had not been provided with information that would have greatly aided their analyses.

Chapter 2: Analysis of Rainfall Patterns

Chapter 2 is devoted to demonstrating that large rainstorms occurred more frequently between 1994 and 1998 than during earlier periods. However, this analysis does not actually address the issue of concern: we need to know whether a rainstorm of a given size is now producing a greater severity of flooding than an equivalent rainstorm would have produced before about 1989. The relevant question is not directly considered by the chapter.

However, photos provided by the report disclose the extent of inundation during several rainstorms of the 1970s, allowing some comparison with flood levels during more recent storms. Unfortunately, the historic photos are taken primarily of the downstream portions of both Elk and Freshwater watersheds, and few images are provided of the reaches immediately upstream that are the current focus of controversy. Photographs during the 18 March 1975 storm (described by the report as the "storm of the century") that do show the reaches of concern (Figures 35, 44, 45) show substantially lower stages than were observed during several floods of 1996-99; the stage shown at the Howard Heights reach on Freshwater Creek and below the confluence of the north and south forks of Elk River is similar to that attained by the storm of 6-7 February 1999. The relevant photo provided for the 16 January 1974 storm (Figure 21; note mislocation of Figures 20 and 21 on Figure 46 of the report) shows a river stage that is only slightly overbank in the reach of interest. It may simply be that the photos were taken for reasons other than to document the extent of flooding, or that they were taken well after the peak, but it may also be possible that these reaches were rarely photographed during the pre-1990 period because flooding was not yet an issue at these locations.

The analysis that would have been expected in the present context is a comparison of rainstorms that did and did not cause flooding before and after the early 1990s. Had such an analysis been carried out, it would have shown that the storm of 6-7 February 1999 consisted of a 2-day rainfall of 2.09 inches and a three-day rainfall of 2.10 inches. In comparison, the 18 March 1975 storm produced a 2-day rainfall of 4.86 inches and a 3-day rainfall of 5.15 inches, and the storm of 16 January 1974 had 1- and 2-day totals of 3.28 and 4.33 inches, respectively. These results suggest that storms of a given size today are producing a greater extent of flooding than storms of larger sizes did in the past.

Although the analysis of storm patterns provided by Chapter 2 does not directly address the issue of concern, results of such an analysis will be useful for other applications. However, several corrections must be made before the results can be applied. One of these changes involves a modification to the method used for analysis to bring it into conformity with standard approaches. The Eureka rain gauge was moved to a new site in 1994, immediately preceding the period during which flooding has become an issue. Any comparison between pre-1994 and post-1994 storms thus depends strongly on the assurance that gauge records at the two sites are functionally equivalent. For example, if the Eureka rain gauge had been moved to site where rainstorms were more intense, comparisons of rainstorm sizes before and after 1994 would necessarily show that recent storms are, on average, larger than earlier storms. Inferences founded on such a comparison would then be invalid unless records are adjusted to compensate for the change in rainfall amounts caused by the change in gauge location. Chapter 2 states that "the move of the Eureka gauge did not have a significant effect on the annual rainfall totals" based on a comparison of the relationship between Scotia rainfall and the 63 pre-1994 annual rainfalls and the relationship between Scotia rainfall and the 5 years of record from 1994 to 1998 (Figure 1). The method used, however, was not a standard approach to such a comparison, and the deviation from the standard method decreases the likelihood of finding a significant difference if one actually exists.

The standard method for such an analysis is described by Dunne and Leopold (1978, p.41): "To check the homogeneity of a station at location A, several nearby stations, known to have a homogeneous record, are selected and their annual totals are averaged for each year. The accumulated average is plotted against the accumulated annual total at station A..." In essence, stations are selected and data analyzed in such a way as to decrease the variance (the "scatter") of the relationship as much as possible. The number of samples needed to identify a change in the relationship increases as the variance of the original relationship increases. For example, if the relationship between two sites is perfect, a single point that deviates from the line would indicate a change, while if the relationship is poorly defined, decades of rainfall records may be necessary to demonstrate an equivalent magnitude of change. In the present case, the rainfall record from a single station located 36 kilometers (22 miles) from the station of interest was selected for comparison instead of an average of records from the several gauges located within 25 kilometers (16 miles) of

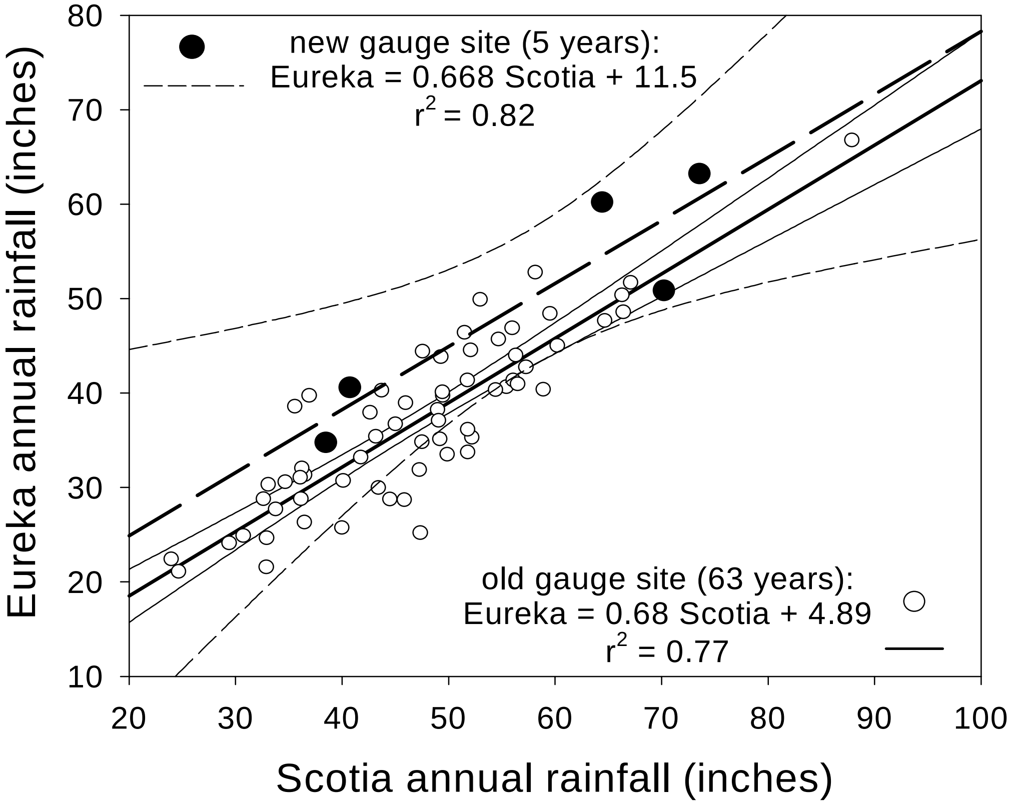


Figure 1. Relation between annual rainfall at Eureka and annual rainfall at Scotia for 1931-1993 (open circles, solid line) and for 1994-1998 (solid circles, dashed line) (from PL 1999). Chow's test and analysis of covariance both indicate that the relationships are significantly different from one another at the 0.05 confidence level. Results suggest that the gauge at the new Eureka gauge site records annual rainfalls that are 6 to 7 inches greater than would have been recorded at the pre-1994 Eureka gauge site.

the station. The high inherent variance of the Scotia:Eureka relationship ensures that no statistically significant difference would be detected from the existing 5 years of rainfall record unless the actual change were very large.

The second correction needed involves the statistical analysis used to compare the relationships for pre- and post-1994 conditions (Figure 1): I was not able to reproduce the results reported in Chapter 2 when I applied Chow's test (Wilson 1978) to the regression results provided in Appendix Table A (PL 1999). The equation used for Chow's test is

$$F\left(n_2, n_1 - p\right) = \frac{n_1 - p}{n_2} \cdot \frac{S_3 - S_1}{S_1} \qquad (1)$$

where n is the number of samples, S is the residual sum of squares, p is the number of parameters estimated in each regression (2 in this case), and the subscript 1 refers to the first data set, 2 to the second data set, and 3 to the combined data sets. Instead of demonstrating that the pre- and post-1994

Table 1. Comparison of rainfall relationships (regression data from PL 1999)

A. Regression information	**Samples**	**Residual sum of squares**
Data from before 1994	63	1163.8
Data from 1994 to 1998	5	105.7
Combined data	68	1417.2
B. Comparison of regressions	**Chow**	**Analysis of covariance**
Calculated F	2.66	3.73
Parameters for critical F	(5,61)	(2,64)
Critical F for p=0.20	1.6	1.5
Critical F for p=0.05	2.37	3.15
p-value	0.031	0.030

records are equivalent at the 0.20 level of significance, as asserted in Chapter 2, the test actually shows that the relationships are significantly different at both the 0.20 and 0.05 levels of significance (Table 1).

The relationships were then reexamined using analysis of covariance (Zar 1984), which is a more appropriate test when the form of the relationship can be assumed to be the same in the two data sets to be compared (J. Lewis, USDA Forest Service Pacific Southwest Research Station, personal communication), as would be expected in the case of rainfall data. The equation used for analysis of covariance is

$$F\left(p, n_1 + n_2 - 2p\right) = \frac{n_1 + n_2 - 2p}{p} \cdot \frac{S_3 - S_1 - S_2}{S_1 + S_2} \qquad (2)$$

The analysis of covariance, too, demonstrates that the relationships are significantly different at both the 0.20 and 0.05 levels of significance. Given the data provided by PL (1999), the annual rainfall at the new Eureka gauge location appears to be approximately 6.6 inches higher than at the previous Eureka gauge location, suggesting that the gauge at the new location records 17% more rainfall during an average year. Because the new location of the gauge is within a mile of the old location, a change is likely to be influenced more by the gauge's catch efficiency or local wind patterns than by a difference in the amount of rain actually falling in the area. Proximity to a tall building, for example, might create wind patterns that locally deflect rain. An additional analysis would need to be carried out to define the relationship between storm rainfalls before and after the gauge was moved.

Thus, not only is the analysis of rainstorm magnitudes provided by Chapter 2 not directly useful for resolving the flooding issue, but it is also based on an invalid assumption. A valid analysis of rainstorm frequencies would require that post-1994 rainstorm sizes be adjusted to reflect the conditions at the new Eureka gauge site.

Chapter 3: Analysis of Rainfall Interception and Runoff

Chapter 3 summarizes studies on rainfall interception loss and runoff to support the argument that a logging would not significantly influence flood peaks in Freshwater and Elk watersheds. However, the information provided by Chapter 3 generally supports the opposite conclusion: that logging in the watershed is likely to have increased peakflows during floods, and that decreased rainfall interception due to logging is one possible mechanism for such a change.

Chapter 3 cites work by Kittredge (1948) to make the point that interception losses expected during small storms separated by warm, dry, weather are likely to be even greater than those during large winter storms. As the calculations provided by Reid (1998) were for large winter storms, the conclusions of Chapter 3 thus suggest that the effect of interception loss may be even greater than that estimated by Reid (1998). Small storms separated by warm, dry, weather tend to occur early in the storm season, and these storms can be important for establishing levels of antecedent soil moisture at the time a later, larger storm occurs. Because flooding levels are partly controlled by antecedent moisture conditions, high rates of interception loss in forests during small, warm-weather storms may delay the onset of susceptibility to flooding by maintaining low levels of antecedent soil moisture for longer into the wet season.

The second portion of Chapter 3 summarizes comments by Patric (1999) which are included in the final chapter of the report (PL 1999); these are discussed below in the review of consultants' reports.

The third portion of Chapter 3 describes other studies. First, the text asserts that studies at Caspar Creek showed that "timber harvest had only a small effect on the magnitude of the large stream flows associated with overbank flooding" (PL 1999). The Caspar Creek study actually showed an average of a 27% increase in the magnitude of 2-year recurrence-interval flood peaks in clearcut tributary watersheds (Ziemer 1998). Second, Chapter 3 cites low rates of interception loss recorded by Rothacher (1963) during winter storms of the Oregon Cascades. However, results of the Rothacher study were already shown not to be applicable to conditions in Freshwater and Elk watersheds because the study was carried out in a non-maritime climate with relatively cold winters (Reid 1999, and see later).

Chapter 3 also makes the point that not all of the logged lands of Freshwater were clearcut. However, calculations by Reid (1998) indicate that hydrologic impacts are likely to exist even when the timing and proportions logged by each silvicultural strategy are considered; calculations were based on the proportional canopy change of 50% for commercial thinning, selection, seed tree preparation, and shelterwood preparation indicated by Chapter 3 to be appropriate. Chapter 3 also notes that not all of the clearcut lands were burned or mechanically prepared, but it does not indicate what proportion of the land was treated with herbicide. Herbicides are applied precisely because they are effective in suppressing regrowth of pioneer species after logging.

Finally, Chapter 3 states that "Regardless of which source is used, the scientific literature documents that harvest conducted as few as 3-5 years ago will be substantially 'recovered' with respect to rainfall interception and runoff." However, a discussion by Mr. J. Patric (Patric 1999), included later in the report (PL 1999), cites evidence that a 35-year-old white pine forest intercepts only 73% of the rainfall intercepted by a 60-year forest (Helvey 1967). A report on rainfall interception in Freshwater watershed (Rains 1971) also notes that a relationship exists between the basal area of a forest stand and the percent of rainfall intercepted. These two data sets plot on the same curve (Figure 2), although data from Appalachian white pine forests are not expected to represent either forest or climate conditions characteristic of California redwood forests. Reid (1999) uses data from Lindquist and Palley (1963) to estimate basal area for redwoods as a function of stand age, thereby allowing an estimate to be made of percentage hydrologic recovery as a function of stand age. For Freshwater Creek, hydrologic conditions characteristic of 80-year-old stands had been found not to present flooding problems. If interception rates for 80-year stands are taken as indicating "fully recovered," then 50-year stands are found to be approximately 89% recovered and 20-year stands only 56% recovered (Figure 3); recovery for 3- to 5-year-old stands would be substantially less

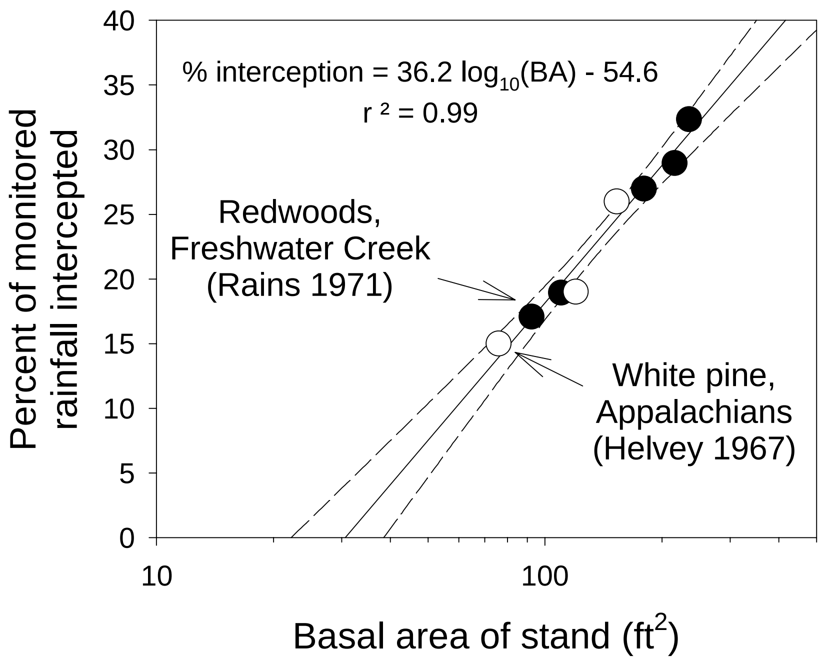


Figure 2. Relationship between stand basal area and percent interception (from Reid 1999)

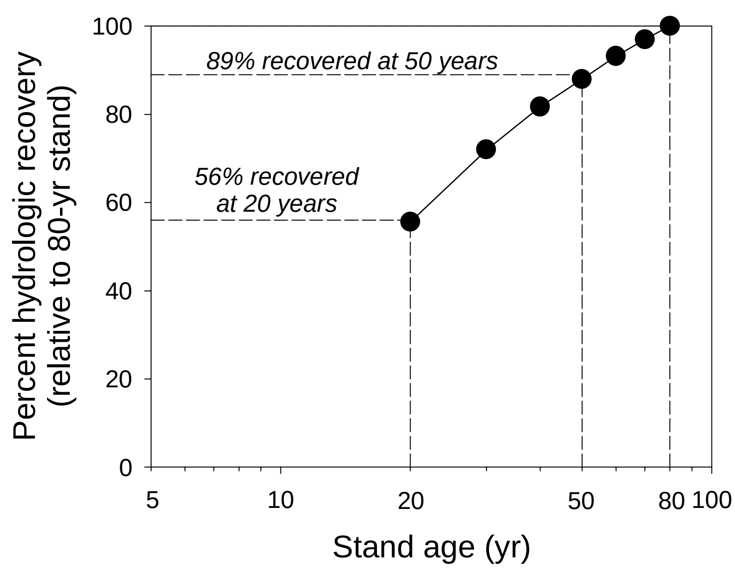


Figure 3. Estimated hydrologic recovery as a function of stand age (f Reid 1999)

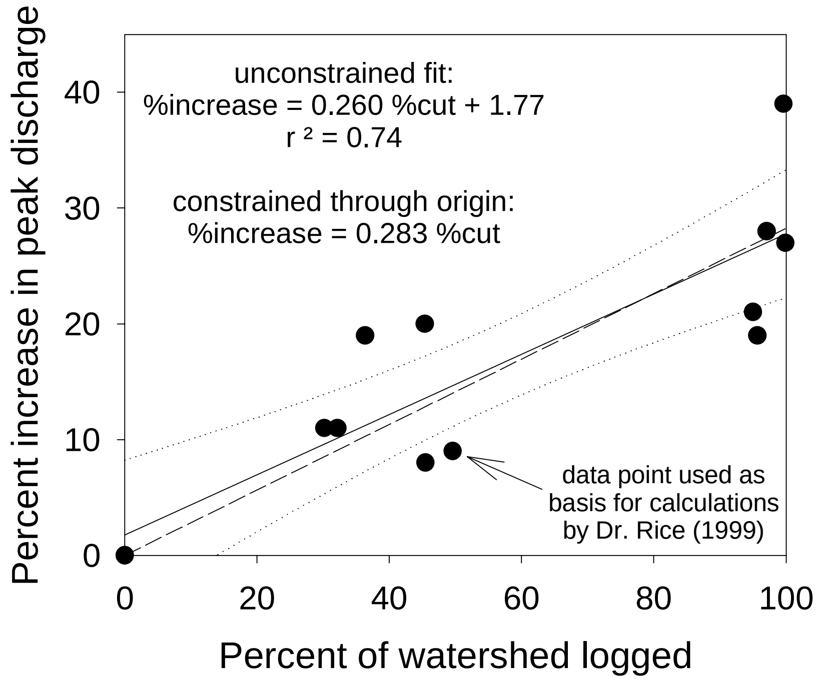


Figure 4. Relationship between peak-flow change and percent of watershed logged for the first 4 to 6 years after logging at Caspar Creek (from Reid 1998). The data point used in Dr. Rice's calculations (Rice 1999, see later) is identified.

than 20%. These results indicate that 3 to 5 years is insufficient for hydrologic recovery, and suggest that the 15-year recovery period assumed during the calculations presented by Reid (1998) may also underestimate the actual time required for recovery.

Results of the Caspar Creek study (Ziemer 1998) also indicate that recovery times are longer than the 3-5 years estimated by PL (1999). Recovery rates for the first 7 years have been on the order of 8% per year (Ziemer 1998). If the rate of recovery is assumed to be uniform through time (i.e., 8% of the original change per year), then 12 to 13 years would be required for complete recovery from peakflow increases.

In addition, four to six years of data were combined to calculate proportional peak-flow increases as a function of percent of watershed cut at Caspar Creek (Reid 1998). The resulting curve (Figure 4) thus represents an average relation for the first four to six years after cutting. The average 27% increase for 2-year recurrence-interval peak flows in clearcut Caspar Creek tributaries thus actually characterizes 2.5-year-old logging, and if the recovery rate of 8% per year is considered, the effect during the first year would amount to a 34% increase in peak flows.

It should also be noted that the Final Environmental Impact Statement/Final Environmental Impact Report prepared for PALCO lands (USFWS and CDF 1999, p. 3.4-22) describes hydrologic recovery to be slow, citing a study that reported little peak flow recovery after 30 years in western Oregon and one that reported 50% hydrologic recovery in 25 years.

Examination of the main points of Chapter 3 thus shows that strong evidence exists that logging is capable of increasing peakflows, and that decreased interception of rainfall after forest cover removal is a potential mechanism for such changes. Data from a redwood forest at Caspar Creek (Ziemer 1998) document an average of a 27% increase in a 2-year recurrence interval peakflow for the first 4 to 6 years after logging, and various studies suggest that hydrologic recovery is expected to require more than 10 years. Furthermore, Chapter 3 indicates that small storms are even more affected by interception loss than large storms, implying that an additional mechanism for increased peakflow changes must also be considered in future calculations: antecedent soil moisture will be higher in cut areas than in forests at the time some major storms occur, thus further increasing potential peakflow volumes.

Chapter 4: Analysis of Sediment and Channel Data

Chapter 4 is organized around five premises which, if true, would lead to the conclusion that logging-related sediment affects flooding:

Premise 1. Logging increases the delivery of sediment to streams
Premise 2. This increased sediment delivery cannot be accommodated by the stream's natural sediment transport capability
Premise 3. Aggradation occurs in the areas where flooding is of concern
Premise 4. Such aggradation has a significant effect on the flood carrying or "conveyance" capacity of the stream
Premise 5. The increase in flooding caused by the reduced conveyance capacity actually leads to the inundation of homes, roads, and other structures that otherwise would not have been flooded.

Chapter 4 addresses each of these premises sequentially under the assumption that "if any one of the above premises can be shown to be untrue, then there is no cumulative impact from logging related sediment on flooding."

Chapter 4 begins the analysis by stating that evidence exists that "All available evidence indicates that premise 1 is true;" logging increases the delivery of sediment to streams.

Next, with respect to premise 2, Chapter 4 describes Rosgen (1996) channel types present in Freshwater and Elk watersheds and suggests that because most of the Freshwater channel system is type F or B, aggradation is unlikely in most of the watershed. Chapter 4 later suggests that 1.9 feet of aggradation has occurred recently in a downstream portion of the Freshwater channel mapped as type F, indicating that significant in-filling can indeed occur in the type F channels of Freshwater Creek in which flooding is of concern.

Chapter 4 also addresses premise 2 by evaluating the likely grain sizes of sediment input, noting that most of the logging-related sediment will be fine-grained and so will travel rapidly through the watershed without being deposited. However, observations of aggradation during recent storms (Reid 1999) indicate that fine-grained sediment is the primary contributor to aggradation along lower Freshwater and Elk. Comparison of cross sections measured in 1975 (USACE 1975) and 1998 (Cafferata and Scanlon 1998) demonstrates that much of the aggradation is occurring on the channel's banks and floodplains. Field observations at USACE cross section XS-5, for example, show deep accumulations of silt and sand around fence posts on the floodplain.

Chapter 4 addresses premise 3 first by citing results of PL's cross-section measurements on tributaries to Freshwater Creek. However, these sections are located upstream of the area of concern for flooding. Chapter 4 then quotes Cafferata and Scanlon (1998) as concluding that "only minor channel aggradation may have occurred in the lower gradient reaches of Freshwater Creek...," but the

Table 2. Summary of cross-section data from the reaches of Freshwater and Elk along which flooding is of concern.

Cross section	Source	Location	Dates	Relevant?	Change in bankfull channel area*
Freshwater XS-3	USACE 1975, Cafferata and Scanlon 1998	Flooding reach	1975-98	Yes	34% decrease
Freshwater XS-5	USACE 1975, Cafferata and Scanlon 1998	Flooding reach	1975-98	Yes	34% decrease
Freshwater XS-7	USACE 1975, Cafferata and Scanlon 1998	Above flooding reach	1975-98	No	6% increase
Freshwater tributaries	PL 1999	Above flooding reach	1996-98	No	**
N.Fk. Elk bridge	PL 1999	Flooding reach	1971-98	Yes	42% decrease
Lower Elk	PL 1999	Flooding reach	11/96-1/98	Yes***	2 of 3 show small decreases**

* Change is calculated as the change in channel cross-sectional area below the original bankfull stage

** Percentage changes for the bankfull channel were not provided by PL (1999) but could be calculated if the figures are digitized

*** These cross sections were established after flooding had become a concern, suggesting that measurements will not reflect the period of most rapid cross-sectional change

chapter does not provide the results calculated from the measurements made by Cafferata and Scanlon (1998). These results show that the "minor channel aggradation" is actually equivalent to a 34% decrease in the cross-sectional area of the bankfull channel along the stream reach where flooding is of concern (Reid 1998). The conclusion that "their analysis clearly failed to reveal evidence of significant channel aggradation" (PL 1999) thus is not supported by the data provided by Cafferata and Scanlon (1998).

The discussion of premise 3 ends with the summary statement that "for premise 3 to be true channel surveys must show that aggradation has occurred. Instead, most of the results presented here show little or no aggradation, or in some cases, document down-cutting of stream channels." However, this summary does not distinguish between cross sections that span the relevant time frame (1970s to 1990s) and locations (lower Freshwater and Elk) and cross sections that span short durations after the major period of aggradation or that are located in reaches where aggradation and flooding are not issues. When these sets of measurements are distinguished from one another, the pattern is clear (Table 2): the only three long-term cross sections located in reaches where increased flooding is an issue (XS-3, XS-5, and N. Fork Elk Bridge) show 34%, 34%, and 42% infilling of the bankfull channel. In the case of the N. Fork Elk Bridge cross section shown in Figure 17 of PL (1999), the bankfull level was not identified. The calculation of a 42% change is based on an assumed bankfull elevation of 88.1 feet for the 1971 sounding on the basis of 1) morphology and 2) an assumption that any cross section provided would include the entire bankfull channel. The 31% change in channel area cited in Chapter 4 for the N. Fork Elk Bridge cross section appears to have been calculated for an arbitrary stage above the original bankfull level; the percentage change thus is controlled by the selection of the arbitrary datum used to compare the cross sections. It is notable that the cross section from the flooding reach of North Fork Elk shows infilling of similar proportion to the cross sections from the flooding reach of lower Freshwater (Table 2).

Cross sections located higher in the watershed in some cases show incision. As Dr. Matt O'Connor points out later in the volume, incision of upstream reaches may be one source for the sediment accumulating farther downstream:

> *"The NFCC [North Fork Caspar Creek] study suggests that the greatest increases in peak flow will occur in relatively small clearcut watersheds drained by Class II or III streams. If sediment is available in these channels, it may be assumed that increased peak flows will generate increased sediment loads (as suggested by Lewis 1998, for NFCC). Also, given the evidence that flow increases diminish downstream as the proportion of forested watershed area tends to increase, it is possible that sediment transport rates in downstream reaches may not increase as much as in the sediment-producing headwater streams. Depending on the channel geometry, hydraulics and sediment size, it may be possible to cause channel aggradation downstream if peak flow increases in downstream reaches are insufficient to transport sediment delivered from channels with higher peak flow increases."* O'Connor (1999, p. 9)

Further, inspection of the three cross-sections installed in the downstream reaches of interest after flooding had already become an issue (Figures 18-20, PL 1999) indicates that two of these show net aggradation even over a 7- to 14-month period, while the third shows little change. The author of Chapter 4 rightfully points out that 14 months of record generally is not sufficient to recognize trends.

Premise 4—the question of whether aggradation has significantly affected channel conveyance—is addressed through the argument that temporary scour during floods may be sufficient to increase conveyance during the flood. For such a phenomenon to make a difference, however, it would require that the aggraded sediment be completely evacuated during the flood peak (and thus not be incorporated into the water column during the flood peak, since the sediment would occupy a similar amount of cross-sectional area while being transported), and then completely replaced on the falling limb of the flood. If this is the case, then rates of soil erosion in the watershed are considerably higher than previously expected, since enough sediment would need to be generated during each storm to refill the temporarily evacuated channel. However, since much of the documented aggradation has occurred on banks and floodplains, where new sediment is rapidly stabilized by vegetation, scour of recently aggraded sediment is not likely to be important. Evidence of significant scour would be present in the form of uprooted bank vegetation after each flood. Instead, the depth of sedimentation is evident after each flood by the presence of buried, but intact, herbaceous vegetation.

Chapter 4 addresses premise 5 by estimating the difference in flow depth (stage) that would be caused by hypothesized depths of aggradation, and compares those differences to levels that would result in flooding at a site on Freshwater and a site on Elk River. Calculations are carried out by simply averaging the change in cross-sectional area over the width of the floodplain, thus making the implicit assumption that water velocity on the floodplain is the same as water velocity in the channel. This assumption is rarely valid. In actuality, water generally flows considerably more slowly across floodplains than through channels, so a reduction in channel capacity can have a disproportionate influence on floodplain water depth. The appropriate calculations are rather complicated, but were carried out and described by Reid (1998) and are described in more detail in Appendix 1 of this review. In this case, the calculations demonstrate that if the original bankfull channel at the Wrigley house site were, on average, 2.9 feet deeper (implying that there has been a 28% decrease in channel area to achieve its present dimensions), a flood that would originally have been at bankfull stage would now have increased in stage by 1.3 feet, and thus be capable of inundating the Wrigley driveway. Had the bankfull channel aggraded by an average of 5.2 feet (implying a 41% decrease in channel area, approximately equivalent to the change documented by PL (1999) on the North Fork Elk River above the confluence), the change would have been sufficient to have increased the stage of what once was a bankfull flow by more than 3 feet. Clearly, if the extent of aggradation observed on the North Fork Elk river above the confluence is also present near the Wrigley house, the change is sufficient to greatly increase the frequency of inundation of homes, roads, and structures during peak flows that would not have previously posed a hazard at the site.

Data presented by PL (1999), in combination with data and analyses presented by Reid (1998, 1999) thus support the validity of all five premises. According to the logical construct proposed by Chapter 4, the conclusion is true that aggradation of logging-related sediment is likely to have increased flood hazard in these watersheds.

Consultant's report: Dr. Matt O'Connor

Dr. O'Connor first provides a summary of the paper by Ziemer (1998), ending with the statement that "no measurements of interception were made in connection with the Caspar Creek study, so no direct analytic investigation of the effect of decreased interception could be conducted." Since that paper was written, however, such measurements have indeed been made and are described by USFWS and CDF (1999; Appendix T) and Reid (1999). These results indicate that 16.8% of the rainfall during a storm of 3.3 inches in a 24-hour period was stored on or evaporated from the forest canopy during the storm. A 3.3"/24 hr storm recurs, on average, once every 2.2 years at Caspar Creek, producing an effective rainfall of 2.8 inches under forested conditions. Under those conditions, a rainfall of 3.85" would be required to produce an effective rainfall of 3.3", and this would occur, on average, once every 4.4 years. When forest cover is removed, an effective rainfall that originally had a 4.4-year recurrence interval will begin to occur, on average, once every 2.2 years. The flooding associated with such a storm, on average, will have increased in frequency by more than a factor of 2, since antecedent moisture levels also will be higher due to the increase in effective rainfall during the preceding, smaller storms. Data from clearcut tributaries of Caspar Creek also indicate that 2- to 4-year recurrence-interval floods are now occurring 1.5 to 2 times as frequently as before logging (J. Lewis, USDA Forest Service Pacific Southwest Research Station, personal communication).

Dr. O'Connor then calculates the proportional change in runoff expected in Freshwater watershed by assuming that the 2-year recurrence-interval peakflow increases by 27% for a completely clearcut watershed. Areas mapped as "forest opening" in vol. 1, p.17 of the SYP (PL 1998) are assumed to generate 27% increases in peak flow, while other forest conditions (including areas that have undergone selective logging and thinning) are assumed to be hydrologically recovered. Because 2/3 of the logging in the watershed has employed silvicultural strategies other than clearcutting, and because these other strategies result in approximately 50% of the canopy loss of clearcutting (PL 1999), Dr. O'Connor's calculations underestimate the actual effect. Dr. O'Connor's Table 2 indicates that under the current baseline conditions, 7% of Freshwater and Elk watersheds are hydrologically immature, implying that only 7% of the forest canopy cover has been removed in the last 10 years. However, data compiled by CDF from Timber Harvest Plans (CDF 1999a, 1999b) indicate that approximately 30% of the forest canopy has been removed from Freshwater watershed during the past 10 years. With this correction, the method suggested by Dr. O'Connor for calculations (Dunne and Leopold 1978) would indicate that the expected flood response is approximately 4.3 times greater than that calculated by Dr. O'Connor for baseline conditions. The effect in future decades will also be significantly greater than indicated by Dr. O'Conner when the appropriate corrections are made.

For example, at the point when 50% of Freshwater's canopy has been removed in the previous 10 years (estimated to be in about 2004, given current cutting trends), the method first would assume that a 13.5% increase in peak flow is expected for the watershed as a whole. Then, using the relationship cited by Dunne and Leopold as being typical "for a large number of basins" (Dunne and Leopold 1978, p.639) the proportional change in flow depth can be estimated from discharge:

$$\frac{D_2}{D_1} = \frac{cQ_2^{0.4}}{cQ_1^{0.4}} = \frac{\left(1.135Q_1\right)^{0.4}}{Q_1^{0.4}} = 1.052 \qquad (3)$$

where D_1 and D_2 are the flow depth before and after the change, Q_1 and Q_2 are the discharges before and after the change, and *c* is a constant. An increase by a factor of 1.052 would be sufficient to bring what had been a 12.8-foot stage to a bankfull level of 13.5 feet at XS-3. Given the regional flood frequency relation for the area and the local channel geometry (Reid 1998), this change would mean that over-bank flooding would occur approximately 1.35 times as often as before the recent timber harvest operations. Results of calculations by Reid (1998), which use an entirely different method that takes into account the characteristic distribution of storm sizes in the area, suggest that over-bank flow frequency would increase by approximately 80%. In either case, the increased frequency of flooding is substantial.

Dr. O'Connor notes that the Freshwater and Elk River watersheds are underlain by weak sedimentary rocks that weather to silt- and clay-sized particles, and suggests that these grain sizes are too readily transported to contribute to aggradation. However, the aggradation observed to have occurred during the flood of 21 November 1998 is primarily of sand-sized and smaller particles which accumulated on the channel banks (Reid 1999). Similarly, partially buried fence posts at XS-5 also show that aggradation at this site has been primarily by fine-grained sediment. Comparison of 1975 and 1998 cross-sections show that much of the aggradation has been on the channel banks, and this information is also consistent with the observation that the aggrading sediments are fine-grained. Dr. O'Connor points out that fine-grained sediment moves rapidly while it is in transport, while coarse sediment can take a long time to travel to a downstream location. That the aggrading sediment is fine-grained is thus a strong indication that the aggrading sediment is derived from on-going activities in the watersheds rather than from historic activities.

In summary, then, Dr. O'Connor's analysis—when modified to reflect the actual rate of canopy removal in Freshwater watershed—supports the conclusion that logging has significantly increased the frequency of flooding along lower Freshwater Creek. Further, his conclusion that aggradation is not likely because sediments are too fine-grained is shown by direct field observations to be in error, and, by Dr. O'Connor's argument, the presence of fine-grained aggradation suggests that on-going activities provide the primary source of aggrading sediment.

Consultant's report: Mr. James Patric

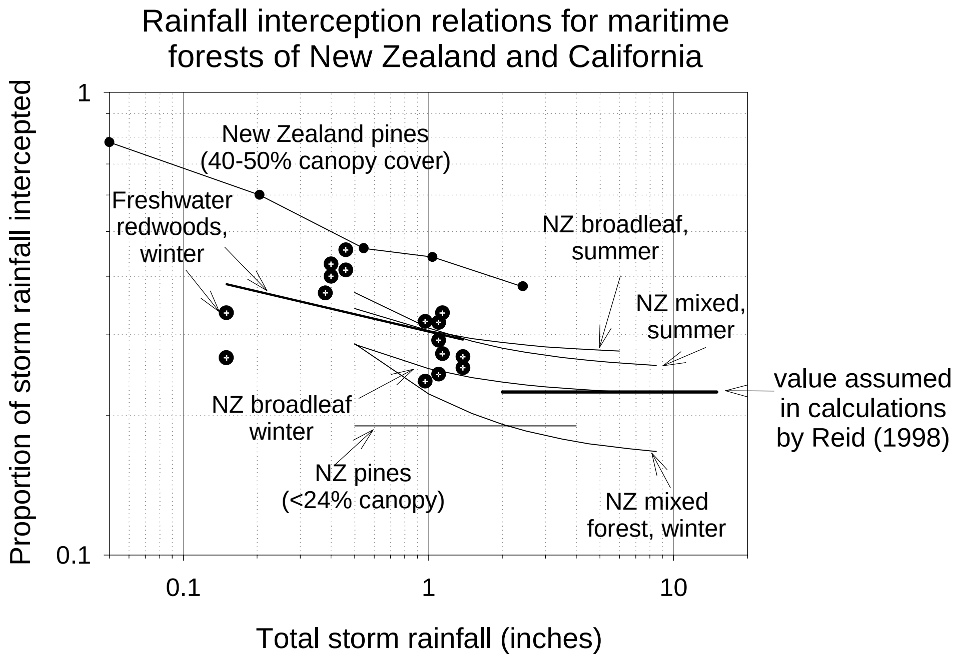
Mr. Patric raises three primary points in his review of Reid's (1998) analysis of foliage interception loss in Freshwater Creek watershed. First, he points out the need to consider interception loss on vegetation remaining or regrowing after logging. Second, he questions the validity of the studies upon which estimates of likely loss rates were based. And third, he asserts that data from

Appalachia and the Oregon Cascades are more likely to be applicable to the California Coast than are data from maritime climates in New Zealand.

Mr. Patric cites data from Appalachian pine forests to support the argument that interception loss rates from understory vegetation and regrowth will largely compensate for decreased interception after logging. This may indeed be the case in forests of eastern North America, where a leaf-area index (which, as a measure of the leaf-surface area available to store water, is expected to influence rainfall interception rates) of 6—reported to be at the upper end of the range for temperate deciduous forests—has been recorded 6 years after a hardwood forest was cleared (Marks 1974). In the Pacific Northwest, however, leaf-area indices are considerably higher, providing substantially more opportunity for evaporation from foliage. A mature Douglas-fir forest, for example, typically has a leaf area index of more than 15 and may attain values as high as 53 (Waring et al. 1978), while understory vegetation in Douglas-fir forests accounts for only 2 to 10% of the total leaf area index (Gholz et al. 1976). Leaf area indices in these forests increase as the forest ages, with increases noted over a 40-year period (Long and Turner 1975). Even if understory vegetation is left intact after logging, if 90 to 98% of the surface area available to store and evaporate water has been removed, interception loss rates will decrease considerably immediately after logging.

Mr. Patric summarizes his argument that regrowth will quickly compensate for forest canopy loss by stating that "...authorities agree unanimously that trees, grass, and agricultural crops intercept rain at very similar rates (Lull 1964, Zinke 1967)," and suggests that interception loss will "...soon become similar to that of mature forest vegetation, perhaps even immediately after cutting." A review of the literature, however, indicates that much work has been devoted to defining differences in interception rates between different vegetation types. Data from chaparral and grasslands in southern California show rates of interception loss to be 1.6 times higher in chaparral than in grasslands (Corbett and Crouse 1968), and significant differences are also noted between hardwood and coniferous forests (Dunne and Leopold 1978). Mr. Patric himself provides a graph of interception loss by a 22-year-old ceanothus-manzanita stand in the Sierra Nevada foothills which shows that this mature chaparral vegetation intercepts only 5% of large storms (Hamilton and Rowe 1949), in contrast to the 16.8% loss measured for a 3.3" day in a coastal redwood forest (USFWS and CDF 1999). It should be noted that ceanothus is a common pioneer shrub in logged redwood forests and is one of the species for which herbicides are targeted.

Forest litter has also been shown to intercept rainfall, but rates of interception by litter must also be accounted for in the original forest; these rates were not considered in Reid's (1998) calculations. Interception by litter will be minimal after burning or mechanical site preparation, so the contrast between effective rainfall in logged and unlogged land may be greater than originally estimated by Reid (1998). Mr. Patric points out that logging slash, too, can intercept rainfall. This mechanism is also disabled by burning and mechanical site preparation.



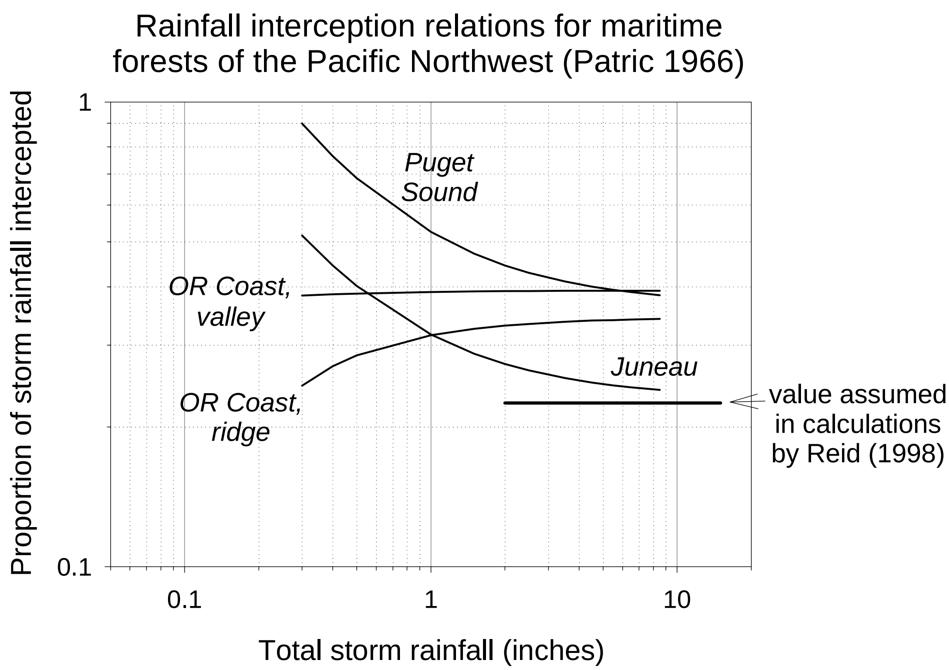


Figure 5. Foliage interception data from maritime climates in New Zealand and California used by Reid (1998) to estimate likely interception rates in Freshwater Creek watershed, and foliage interception relations presented by Patric (1966) for maritime climates in Alaska, Washington, and Oregon. Relations provided by Patric (1966) show consistently higher interception rates than those used in calculations by Reid (1998).

Table 3. Interception relationships for maritime forests in the Pacific Northwest, as calculated by Patric (1966). Relations are plotted in Figure 5. The relation from Rothacher (1963) was not included here because it was based on results from an inland forest.

Location	Source	Regression equation (y = throughfall, x = rainfall)
Washington, Puget Sound	Chowdappa 1960	y = 0.635x - 0.16
Oregon coast, valley	Isaac 1946	y = 0.607x + 0.003
Oregon coast, ridge	Isaac 1946	y = 0.655x + 0.03
Alaska, Juneau	Patric 1966	y = 0.77x - 0.086

Mr. Patric's second argument appears to be founded on his opinion that "Interception loss by New Zealand pines with scant (40-50%) canopy cover seems overly high; ranging from 28 to 78%, it is unprecedented in other experience." He summarizes this conclusion in a later statement that the New Zealand studies incorporate "apparently irrational results." However, work published by Mr. Patric in 1966 (Patric 1966) documents his own measurements of interception loss in coastal Alaska that show even higher rates of interception loss than those observed in New Zealand, and in his paper he cites work of others who observed rates that were higher still. Mr. Patric summarizes the results of his 1966 study with the statement, "Throughfall in the mature coniferous stand near Juneau differed little from that reported in other mature rain forests of western North America (Table 1 [reproduced here in part as Table 3]). Therefore, if the tabulated studies are regarded as random samples from a single forest population, additional throughfall measurements are not needed." In the paper, he provides equations calculated for the other data sets he quotes (Table 3). When plotted (Figure 5), it is evident that Mr. Patric's results, as well as those of the other studies he quotes, would result in a significantly higher estimate of interception loss than that used in the analysis by Reid (1998).

Finally, Mr. Patric argues that data from maritime climates of New Zealand are not applicable to the northwest California coast, while data from Appalachia and the Oregon Cascades are. However, Mr. Patric provides information that allays the concern he raises: "Presumably, energy for evaporation in excess of rates predicted by the Penman equation was made possible by warm prevailing winds blowing from the nearby Pacific Ocean." It is for this reason—that maritime climates are likely to result in different evaporation regimes than montane and continental climates—that data from maritime climates were used in the analysis rather than data from montane and continental climates. A comparison of average monthly temperatures in Eureka, the Golden Downs Forest of New Zealand, and the H.J. Andrews Forest of the Oregon Cascades (Figure 6) also shows that winter temperature distributions at the New Zealand site are more similar to those of Eureka than are those of the Oregon Cascades.

Mr. Patric's major concerns are thus allayed by evidence he has provided: the measurements he cites for other vegetation types show lower interception losses than those measured in coastal forests, his measurements from coastal forests in Alaska and those he cites from other coastal forests (Patric 1966) show higher interception loss rates than those estimated for coastal forests in California, and he provides an explanation for why interception losses are high in coastal forests.

Consultant's report: Dr. Ray Rice

Dr. Rice uses as an example an 80-ft^2 channel running through a 1000-ft-wide floodplain to calculate the influence of a 10% increase in peak flow, indicating that such a change would contribute

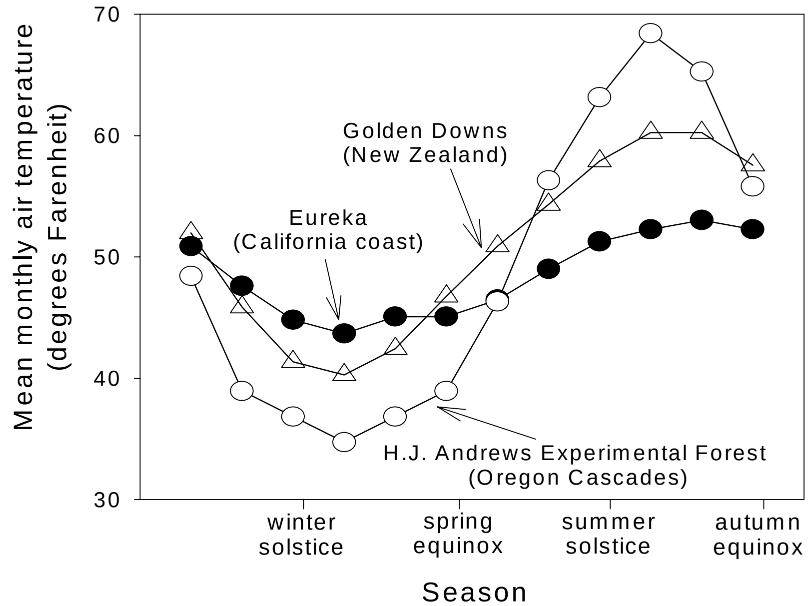


Figure 6. Comparison of mean monthly temperature at Eureka, Golden Downs forest in New Zealand, and H.J. Andrews Forest in the Oregon Cascades.

to an increased stage of only 1/10th inch. In actuality, however, at the lowermost USACE/CDF cross section (XS-3, illustrated in Figure A4-1A of Reid 1998), Freshwater Creek has a bankfull cross-sectional area of about 700 ft^2 and a combined floodplain and channel width of about 400 ft. Given the value of channel roughness characteristic of the site, a 10% increase in peak-flow discharge would lead to a 4-inch increase in stage at this site, rather than the 1/10th inch predicted for Dr. Rice's hypothetical channel. In addition, the regressed relationship for peak flows at Caspar Creek (Reid 1998) indicates that Dr. Rice's calculation would need to incorporate an expected 15% increase in peak flow (based on a 13.5% increase for a half-logged basin, as indicated by the regression), rather than a 10% increase (based on a value of 9% recorded for a single data point among the 11 comprising the data set for partially logged watersheds—this point is identified in Figure 4). With this correction, the expected increase in stage would be approximately 6 inches. Note that this calculation produces an estimate of the increased stage above bankfull, while that carried out using Dr. O'Connor's approach produces an estimate of the increase in stage required to achieve a bankfull stage, since equation (3) can be applied only to flows below bankfull stage.

Dr. Rice next addresses the question of sediment input. However, the sediment calculations presented by Dr. Rice are not consistent with volumes found to have been introduced into the North Fork Elk River by PWA (1998). In contrast to the total PALCO input of 3549 yd^3 estimated by Dr. Rice for both forks of Elk River in a 10-year period (equivalent to about 9 yd^3/mi^2-yr), PWA (1998) found that 32,497 yd^3 had been delivered just to the North Fork Elk River from road-related erosion alone in only a 7-year period (equivalent to about 207 yd^3/mi^2-yr). Landslides, from which approximately 80% of the input is associated with logging (Michlin 1998), were found to contribute considerably more sediment than road-related erosion over the same period (PWA 1998), suggesting that Dr. Rice's estimates may under-represent logging-related sediment inputs by two orders of magnitude. The PWA (1998) data suggest that, rather than providing a 2% increase in the Elk River sediment load, logging-related sediment actually has accounted for sediment loads in North Fork Elk that are more than 100% greater than background rates.

Consultant's report: Dr. Marvin Pyles

Dr. Pyles notes that Ziemer (1998) documents increased peak flows following logging in Caspar Creek, and notes also that the proportion of a watershed cut is an important influence on the magnitude of the impact of logging on downstream flood peaks. It is for this reason that the calculation provided by Reid (1998) is based on the documented proportion of Freshwater watershed that was recently cut.

Further, Dr. Pyles indicates that changes in channel capacity may have a major influence on flood hazard at a site, and that "site specific assessments of channel capacity will have to be made to determine the impact of sediment on flooding." This is precisely the analysis provided by Reid (1998, 1999), which indicated that the observed levels of sedimentation in lower Freshwater Creek are likely to lead to a 2-fold increase in frequency of what had once been a 10-year recurrence interval flood.

Suggestions for watershed assessment

The issues raised by the report (PL 1999) indicate the questions that would be useful to address during assessments that soon will be carried out for Freshwater and Elk watersheds. Several kinds of analyses might be considered for inclusion in the assessments to help address those questions:

To what extent have the Freshwater and Elk channels aggraded?

1. Interview residents along various channel reaches to obtain descriptions of timing and magnitude of observed changes
2. Obtain cross-section notes from the other four Army Corps cross sections of Freshwater, and resurvey those sections
3. Relocate the USGS gauge site on Elk, and resurvey that cross section
4. Excavate partially buried vegetation along both creeks and date the development of adventitious roots
5. Excavate this year's deposits to measure deposit depths while buried herbaceous vegetation is still evident
6. Probe channel beds for depths to cobble and pebble layers, if present
7. Assess depths of deposits around datable structures, such as fence posts
8. Compile the above information to identify the sizes and settings of streams most susceptible to accelerated aggradation

To what extent has channel change influenced flooding depths?

1. Determine values of Manning's n from Elk River gauging records
2. Calculate conveyance and flow depths for original and existing cross sections using results from channel aggradation measurements
3. Map depth or extent of flooding along the channels during several moderate to large events

What sources of sediment are influenced by logging and road management, and how much are sediment inputs affected?

Landslides

1. Compare landsliding rates for a single large storm on cuts of different ages
2. Compare landsliding rates on cut areas and in forests
3. Analyze landsliding rates by silvicultural method
4. Analyze landsliding rates by site type
5. Analyze landsliding by storm size
6. Compare rates of landsliding downslope of forested and cut areas

(note that these analyses should be done over a broad area to provide a large enough sample size; this may require grouping data from the same rock type in multiple watersheds)

Surface erosion (logging)

1. Map extent of rilling on cable trails
2. During a large storm, map the extent of overland flow on cable trails
3. During a large storm, map the extent of overland flow on tractor trails
4. Install overland flow traps to determine whether flow has occurred during specific storms

Surface erosion (roads)

1. At the end of the wet season, map the extent of rilling on seasonal roads
2. At the end of the wet season, map the extent of rilling on skid roads
3. Monitor culvert or water bar effluent during storms along roads of different substrate, use level, and surfacing material

Gullying of Class III channels

1. After a series of large storms, compare the morphology and extent of Class III channels as a function of age of logging
2. Compare the morphology of Class III channels as function of woody debris loadings
3. Compare age and load of woody debris in Class III channels in undisturbed forest and forests logged at different times

Road-related landsliding and gullying

1. After large storms, compare rates of landsliding and gullying on roads that have been "storm-proofed" and those that have not

To what extent could the road network influence watershed hydrology?

1. Map drainage paths from road-surface drainage on a variety of road types, substrates, and road locations during large storms

Clearly, some of the suggested analyses can only be done during particular field conditions (e.g. during large storms) or seasons (e.g. at the end of the wet season), and these restrictions may make it difficult to incorporate the analyses into assessments that are expected to be completed over the short term. However, if such work is initiated when conditions are appropriate, results will eventually be available to help answer questions left unresolved by the assessments. Results would also be available in time to be applied to assessments scheduled for later.

References

Cafferata, P.H., and H. Scanlan. 1998. Freshwater Creek cross-section remeasurement. Memorandum to Mr. Dave Ebert, Ranger Unit Chief, Humboldt-Del Norte Ranger Unit, dated 11 September 1998.

CDF [California Department of Forestry and Fire Protection]. 1999a. Freshwater Creek watershed silvicultural practices. Map prepared by Coast-Cascade GIS, Santa Rosa, CA.

CDF [California Department of Forestry and Fire Protection]. 1999b. Eureka Plain Hydrologic Unit timber harvest activity 1988-1999. Map prepared by Coast-Cascade GIS, Santa Rosa, CA.

Chowdappa, P. 1960. A study of interception, stemflow, and litterfall in some plantations in Pack Forest. MS Thesis, University of Washington, Seattle. 50 pp.

Corbett, E.S., and R.P. Crouse. 1968. Rainfall interception by annual grass and chaparral...losses compared. USDA Forest Service Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. Research Paper PSW-48.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company, San Francisco, CA.

Gholz, H.L.; F.K. Fitz, and R.H. Waring. 1976. Leaf area differences associated with old-growth forest communities in the western Oregon Cascades. Canadian Journal of Forest Research 6:49-57.

Hamilton, E.L., and P.B. Rowe. 1949. Rainfall interception by chaparral in California. Division of Forestry, Sacramento, CA.

Helvey, J.D. 1967. Interception by white pine. Water Resources Research 3(3): 723-729.

Isaac, L.A. 1946. Fog drip and rain interception in coastal forests. USDA Forest Service Research Note 34. Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Kittredge, J. 1948. Forest influences. McGraw-Hill Book Co., New York.

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds. Pp. 55-70 in R.R. Ziemer (technical coordinator), Proceedings of the conference on coastal watersheds: the Caspar Creek Story. USDA Forest Service Pacific Southwest Research Station General Technical Report PSW-GTR-168.

Lindquist, J.L., and M.N. Palley (1963) Empirical yield tables for young-growth redwood. California. Division of Agricultural Sciences, University of California. Agricultural Experiment Station Bulletin 796.

Long, J.N., and J. Turner. 1975. Aboveground biomass of understorey and overstorey in an age sequence of four Douglas-fir stands. J. Applied Ecology 12:179-188.

Lull, H.W. 1964. Ecological and silvicultural aspects. Pg. 6-1 to 6-30 in: V.T. Chow (ed), Handbook of applied hydrology. McGraw-Hill Book Co., New York.

Marks, P.L. 1974. The role of pin cherry (*Prunus pensylvanica* L.) in the maintenance of stability in northern hardwood forests. Ecological Monographs 44: 73-88.

Michlin, L. 1998. Letter addressed to Mr. Tom Herman, Pacific Lumber Company, dated 8 October 1998, from the California Regional Water Quality Control Board.

O'Connor, M. 1999. Re: Potential peak flow changes for Freshwater Creek and Elk River watersheds and considerations regarding potential effects of channel sedimentation on peak flow magnitude and frequency. In: Pacific Lumber Company, An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California. Pacific Lumber Company, Scotia, CA.

Patric, J.H. 1966. Rainfall interception by mature coniferous forests of southeast Alaska. Journal of Soil and Water Conservation 21(6):229-231.

Patric, J.H. 1999. Letter to J.C. Barrett. In: Pacific Lumber Company, An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California. Pacific Lumber Company, Scotia, CA.

PL [Pacific Lumber Company]. 1998. Sustained yield/Habitat Conservation Plan for the properties of The Pacific Lumber Company, Scotia Pacific Holding Company, and Salmon Creek Corporation. Public Review Draft.

PL [Pacific Lumber Company]. 1999. An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California. Pacific Lumber Company, Scotia, CA.

PWA [Pacific Watershed Associates]. 1998. Sediment source investigation and sediment reduction plan for the North Fork Elk River watershed, Humboldt County, California. Report prepared for The Pacific Lumber Company. Pacific Watershed Associates, Arcata, California.

Rains, M. 1971. Interception of rainfall by a redwood canopy in the north coast of California. M.S. Thesis, Humboldt State University, Arcata, CA. 100 p.

Reid, L.M. 1998. Review of the Sustained Yield Plan / Habitat Conservation Plan for the properties of The Pacific Lumber Company, Scotia Pacific Holding Company, and Salmon Creek Corporation. Report prepared for the Environmental Protection Agency and for Congressman George Miller.

Reid, L.M. 1999. Review of the Final EIS/EIR and HCP/SYP for the Headwaters Forest Project. Report prepared for Congressman George Miller.

Rice, R.M. 1999. Letter to Dr. J.C. Barrett. In: Pacific Lumber Company, An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California. Pacific Lumber Company, Scotia, CA.

Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Rothacher, J. 1963. Net precipitation under a Douglas-fir forest. Forest Science 9:423-429.

USACE [U.S. Army Corps of Engineers]. 1975. Flood plain information, Freshwater Creek, Humboldt County, California. Prepared for Humboldt County by the US Army Engineer District, San Francisco. Corps of Engineers.

USFWS and CDF [United States Fish and Wildlife Service and the California Department of Forestry and Fire Protection]. 1999. Final Environmental Impact Statement/Environmental Impact Report and Habitat Conservation Plan/Sustained Yield Plan for the Headwaters Forest project. Public Review. United States Fish and Wildlife Service and the California Department of Forestry and Fire Protection.

Waring, R.H.; W.H. Emmingham, H.L. Gholz, and C.C. Grier. 1978. Variation in maximum leaf area of coniferous forests in Oregon and its ecological significance. Forest Science 24:131-140.

Wilson, A.L. 1978. When is the Chow test UMP? The American Statistician 32(2): 66-68.

Zar, J.H. 1984. Biostatistical analysis. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Ziemer, R.R. 1998. Flooding and stormflows. Pp. 15-24 in R.R. Ziemer (technical coordinator), Proceedings of the conference on coastal watersheds: the Caspar Creek Story. USDA Forest Service Pacific Southwest Research Station General Technical Report PSW-GTR-168.

Zinke, P.J. 1967. Forest interception in the United States. Pg. 137-161 in: Sopper, W.E. and H.W. Lull (eds.), Forest hydrology. Pergamon Press, New York.

Appendix 1. Calculation of stage from cross section data

Appendix 4 of Reid (1998) describes the method used to calculate the increase in stage expected from a given change in channel cross-sectional area or discharge. The method is again described here, but in greater detail. The calculations described below are necessary because what appears to be the simple solution to the problem is not valid: one cannot simply calculate the area lost to the cross section (say, 100 ft^2) and average that area over the width of the floodplain (say, 500 ft) to calculate the change in stage (100 ft^2/500 ft). That approach is not valid because it employs the invalid assumption that average water velocity on the floodplain is the same as average water velocity in the channel. In reality, water generally flows considerably more slowly across floodplains than through channels, so a reduction in channel capacity can have a disproportionate influence on floodplain water depth. Calculation of stage change requires that the dependence of flow velocity on flow depth and roughness be accounted for, and the method described below is used to account for that dependence.

1. Plot cross sections

Survey data are first used to plot the channel cross section (e.g., Figure A-1) at each cross-section location. Bankfull stage and other stage heights for which calculations are to be made are identified on each cross section. The location of these points on the cross section is interpolated, if necessary (e.g., the margins of flood inundation shown on Figure A-1). Cross-sectional areas for each stage can now be calculated by summing the areas of polygons defined by the stage elevations and each sequential pair of surveyed or interpolated points (e.g., the areas of the polygons shown in Figure A-1 would be summed to calculate cross-sectional area for the flood height shown).

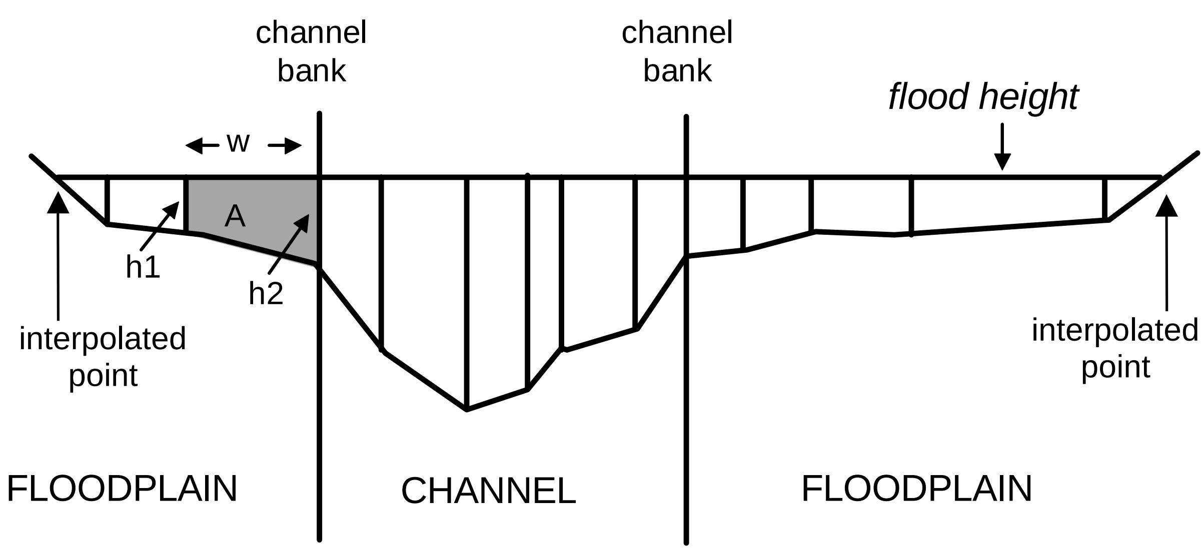


Figure A-1: Example of hypothetical cross section used to calculate discharge for a given stage height. Discharge is calculated independently for each segment of the channel cross section (e.g. shaded area) and results are summed across the channel. Different roughness values can be applied to channel and floodplain flows.

2. Estimate roughness characteristics

In the case of Freshwater Creek, cross-sectional data can be used in conjunction with discharge estimates provided by USACE (1975) to estimate the channel and floodplain roughness characteristics at the stages for which discharge information is given at each of three cross sections. Discharge has been described for the 100-year flood (USACE 1975), and the required information about channel form is known. This information is sufficient to calculate the average roughness factor for the 100-year flood.

First, each cross section is partitioned into sections of overbank flow and in-channel flow. The reported stage of the 100-year recurrence interval flood at each site is used to calculate average depth for that discharge on the floodplain and in the channel, and these depths are assumed to approximate the hydraulic radius *(R)* for each component of the flow (Dunne and Leopold 1978, p.592). The Manning's roughness values *(n)* for the floodplain and channel are first assumed to be equal, and each is described by Manning's equation:

$$n = \frac{1.49 R_f^{2/3} S^{1/2}}{u_f} \qquad (1)$$

$$n = \frac{1.49 R_c^{2/3} S^{1/2}}{u_c} \qquad (2)$$

where *S* is the energy gradient, as approximated by the water surface gradient (noted in USACE 1975), and u_f and u_c are the average velocities for floodplain flow and channel flow, respectively.

The discharge *(Q)* for the 100-year flood is also known, and must equal the sum of the floodplain and in-channel components of the flow, which are themselves equal to the product of the velocity and cross-sectional area *(A)* for each component:

$$Q = u_f A_f + u_c A_c \qquad (3)$$

There are thus three equations and three unknowns, allowing solution for the flow velocities and the

Table A-1. Characteristics at locations of measured cross sections along Freshwater Creek (from USACE 1975)

	XS-3	XS-5	XS-7
Drainage area (mi^2)	28.5	20.9	15.9
Water-surface slope	0.0026	0.0044	0.0042
100-year discharge (cfs)	9500	7400	5700
100-year cross-section area (ft^2)	2417	1345	1362
100-yr width (ft)	550	350	274
overall Manning's *n*	0.062	0.049	0.084
field estimate of channel *n**	0.045-0.059	0.045-0.052	0.060-0.070

* Values estimated by comparison of channel and floodplain characteristics observed in the field (October 1998) with those depicted by Barnes (1967)

Table A-2. Test of the sensitivity of discharge calculations to values of Manning's n. Calculations are made for uniform values of n on floodplain (n_o) and channel (n_c), and for the highest and lowest values of n estimated in the field for each cross section. The Manning's n for overbank flow (n_o) is back-calculated from the 100-yr discharge, given the estimated value of n for in-channel flow (n_c).

XS-3				XS-5				XS-7			
	% discharge change				% discharge change				% discharge change		
Stage (ft)	n_c=0.062 n_o=0.062	n_c=0.045 n_o=0.3	n_c=0.059 n_o=0.068	Stage (ft)	n_c=0.049 n_o=0.049	n_c=0.045 n_o=0.064	n_c=0.052 n_o=0.041	Stage (ft)	n_c=0.084 n_o=0.084	n_c=0.06 n_o=0.24	n_c=0.07 n_o=0.12
38.8	-24	-33	-25	49	-38	-34	-41	75	3	6	4
38	-26	-34	-27	48.2	-38	-35	-41	74	4	7	6
37	-29	-35	-31	47	-34	-32	-36	73	7	10	8
36	-33	-37	-35	46	-43	-42	-44	72	9	13	11
35	-34	-37	-37	45	-52	-52	-52	71	14	16	15
34	-35	-38	-38	44	-72	-72	-72	70	23	24	23
33	-28	-31	-31	43	-80	-80	-80	69	41	41	41
32	-30	-34	-34	42	-90	-90	-90	68	61	61	61

roughness factor at each cross section. Results suggest overall roughness factors on the order of 0.05 to 0.085 (Table A-1).

Values of Manning's *n* were also estimated by comparing the Freshwater Creek channel with photographs of channels having known values of *n* (Barnes 1967). Illustrated channels similar to Freshwater at XS-3 showed *n*-values of 0.045 (Barnes 1967, p.130) to 0.059 (p.178). XS-5 was not directly accessible because the landowner could not be found, but the channel 3700 feet upstream at Steele Lane Bridge was similar to channels with *n*-values of 0.045 (p.130) to 0.052 (p.144); this site appears smoother than XS-3 because of the greater height of bank that is lacking vegetation. In addition, the site of XS-5 supports a more complete riparian canopy than at XS-3 and undergrowth is not dense; channel-bank vegetation is sparse compared to the other locations, and channel roughness is thus expected to be lower. XS-7 was comparable to channels with measured values of 0.060 (p.188) to 0.070 (p.200).

Comparison of the field-based estimates and calculated estimates of Manning's *n* suggests that the values calculated for the 100-year flood are likely to provide reasonable estimates, also, for the in-channel portion of the flood at XS-3 and XS-5. At XS-7, however, overall roughness is greater than that estimated for the channel, suggesting that overbank flow conditions are influential at this site. The single example of an overbank flow illustrated by Barnes has an *n* of 0.097 for the floodplain flow, which passed through a dense stand of hardwoods with diameters of up to 6" (Barnes 1967, p.138). Although the upper channel banks at XS-3 and XS-7 are densely overgrown by brambles and alders, the floodplains are relatively smooth, the first being a grazed pasture and the second a mown lawn and parking lot. In contrast, the floodplain at XS-5 is wooded, but less densely so than that depicted by Barnes on p.138, and overflow channels maintain a sparsely vegetated, channel-like character. Overbank roughness is expected to be substantially lower than 0.097 at each cross section. However, XS-7 is located along a floodplain that is widening after an upstream constriction; flow at this location thus diverges across the floodplain. It is likely that the anomalously high roughness at XS-7 reflects the decreased velocity imposed by the diverging flow paths rather than the properties of the floodplain surface.

For XS-3 and XS-5 the principal contribution to roughness appears to be riparian vegetation, and the 1959 topographic map depicts a distribution of riparian vegetation and pasture that appears identical to that present now at the cross section sites. Aerial photographs taken in the early 1960s show the same pattern. If the same values of Manning's n are expected for two surveys of a given cross section, results of flow calculations for the two surveys are not particularly sensitive to inaccuracies in the estimate of the value of n; the proportional change in flow will be similar. To test this sensitivity, discharges were calculated for cross sections shown by USACE (1975) and Cafferata and Scanlon (1998) assuming channel roughnesses equal to the maxima and minima of the ranges of values estimated in the field and shown in Table A-1. In each case, solution for the reported 100-year discharge allowed back-calculation of the roughness value for the overbank flow. Calculations were then carried out separately for overbank and in-channel components of the flow, and values were summed to calculate total discharge at each stage. Values calculated for 1975 and 1998 cross sections using this approach were then compared to those calculated assuming a uniform value of n for floodplain and channel. The percentage change in discharge that can be conveyed at each stage is shown in Table A-2. In each case, results of each method show the same pattern, suggesting that refinement of estimates of Manning's n would not strongly affect the results.

Roughness values characteristic of the XS-3 site are expected to be characteristic of lowland channels with hardwoods and brambles on banks, and with floodplains largely cleared of forest.

3. Calculate stage for given discharge and cross section

Once the roughness parameters are estimated, Manning's equation can be used to calculate the stage for any discharge at a cross section using an iteration procedure. A value of stage is first guessed. Calculations are carried out for each cross-sectional segment (e.g., the shaded segment in Figure A-1). Average depth for the i^{th} segment is calculated as the average of depths at each end of the segment (e.g., 0.5*($h1$+$h2$) in Figure A-1), and this value is used for R in Manning's equation to calculate average velocity for the segment, where n and S are known:

$$u_i = \frac{1.49\left(0.5\left(h1_i + h2_i\right)\right)^{2/3} S^{1/2}}{n} \qquad (4)$$

The segment's average velocity is multiplied by the segment's cross-sectional area (w*0.5*($h1$+$h2$) in Figure A-1) to calculate discharge for the segment. These values are summed across the width of flow to calculate total discharge. The resulting discharge is then compared to the discharge for which the stage is to be determined, and the value of stage is adjusted accordingly to allow the next calculation to better approximate the desired discharge. This procedure is repeated until the calculated discharge approximately equals that for which the stage was to be calculated.

4. Example: Wrigley house site calculations

As an example, calculations were carried out for the cross section measured at the Wrigley house site and depicted as Figure 21 in PL (1999, in the chapter on "Analysis of Sediment and Channel Data"). Because of the similarity of the conditions at that site to those at XS-3 on Freshwater Creek (USACE 1975), a Manning's n of 0.062 (Reid 1998) and a channel slope of 0.0042 (USACE 1975) were assumed to apply also to the Wrigley house site. Calculations were first carried out for present conditions to determine the discharge required to inundate the Wrigley driveway, located 1.3

feet above current bankfull stage. To determine the depth of channel infill that would have been required to alter what originally was a bankfull flow to one deep enough to inundate the driveway, calculations were carried out for progressively deeper channels until a depth was encountered that accommodated the same discharge within the original channel's banks. Results show that if the original bankfull channel at the Wrigley house site were, on average, 2.9 feet deeper (implying that there has been a 28% decrease in channel area to achieve its present dimensions), a flood that would originally have been at bankfull stage would now have increased in stage by 1.3 feet, and thus be capable of inundating the Wrigley driveway.

A second set of calculations was carried out to determine what change in flood stage would have resulted from a 41% decrease in channel area, a value similar to that which had been documented by PL (1999) on the North Fork Elk River above the confluence. A channel cross section representative of the unaggraded channel was first constructed by assuming that the 41% decrease occurred uniformly across the channel to produce the existing cross section. The bankfull discharge was then calculated for the estimated original channel form. This discharge was then applied to the existing channel form to calculate the flood stage it would produce, using the method described above. Results indicate that the change would have been sufficient to have increased the stage of what once was a bankfull flow by more than 3 feet.

References

Barnes, H.H., Jr. 1967. Roughness characteristics of natural channels. US Department of the Interior, Geological Survey. US Government Printing Office, Washington, D.C. Geological Survey Water-Supply Paper 1849.

Cafferata, P.H., and H. Scanlan. 1998. Freshwater Creek cross-section remeasurement. Memorandum to Mr. Dave Ebert, Ranger Unit Chief, Humboldt-Del Norte Ranger Unit, dated 11 September 1998.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company, San Francisco, CA.

PL [Pacific Lumber Company]. 1999. An analysis of flooding in Elk River and Freshwater Creek watersheds, Humboldt County, California. Pacific Lumber Company, Scotia, CA.

Reid, L.M. 1998. Review of the Sustained Yield Plan / Habitat Conservation Plan for the properties of The Pacific Lumber Company, Scotia Pacific Holding Company, and Salmon Creek Corporation. Report prepared for the Environmental Protection Agency and for Congressman George Miller.

USACE [U.S. Army Corps of Engineers]. 1975. Flood plain information, Freshwater Creek, Humboldt County, California. Prepared for Humboldt County by the US Army Engineer District, San Francisco. Corps of Engineers.