Using Caspar Creek Flow Records to Test Peak Flow Estimation Methods Applicable to Crossing Design[1]

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Abstract

Long-term flow records from sub-watersheds in the Caspar Creek Experimental Watersheds were used to test the accuracy of four methods commonly used to estimate peak flows in small forested watersheds: the Rational Method, the updated USGS Magnitude and Frequency Method, flow transference methods, and the NRCS curve number method. Comparison of measured and calculated results for 10-year return-interval flows demonstrates that, under the conditions tested, the direct flow transference method provides the most reliable results if suitable data are available; results for 100-year flows show similar patterns. None of the methods consistently underestimated the values derived from the gaging record. This indicates that these methods are unlikely to result in an under-design of drainage structures with respect to flow capacity. However, design of stable stream crossings in steep forested areas also requires consideration for passage of sediment, woody debris, and fish, so estimation of required flow capacity represents only a first step in the design process.

Keywords: culvert sizing, flow estimation methods, forest hydrology, watercourse crossings

Introduction

The California Forest Practice Rules require that new or replaced watercourse crossings associated with commercial timber operations on non-federal forestlands in California be designed to accommodate the 100-year flood and its associated sediment and debris. Registered Professional Foresters (RPFs) must estimate the 100-year flood discharge using flow measurement records and empirical relationships; then they must determine if that estimate is reasonable based on actual channel cross-section measurements (CAL FIRE 2016). A variety of methods have been developed over the past 150 years to estimate peak flows in urban watersheds to aid in design of drainage structures (Tolland et al. 1998). However, estimating large peak flows in small, ungaged forested watersheds is difficult because these sites often have steeper slopes and higher infiltration capacities than the sites for which the estimation methods were originally developed.

Refinement of existing methods is a high priority, since appropriate design of stream crossings for roads in forested watersheds is critical for reducing sediment inputs to streams and for decreasing road maintenance and repair costs (Furniss et al. 1998, Weaver et al. 2015). Past monitoring work in California forestlands has shown that crossings are high-risk sites for sediment delivery to streams (Ice et al. 2004, Staab 2004).

The most direct way to test the validity of existing peak-flow estimation methods is to compare predicted and measured flows at stream gaging stations. Few small forested watersheds have gaging records long enough for such testing (Forest Service Stream-Simulation Working Group 2008), but long-term records are available from the Caspar Creek Experimental Watersheds. We use those data to test the accuracy of four methods commonly used to estimate peak flows in forested watersheds in

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the redwood region. This study expands on work reported by Cafferata et al. (2004) and Cafferata and Reid (2013), and updated by Cafferata et al.[4]

Study Site

The North Fork Caspar Creek Experimental Watershed (fig. 1) is located in the northern part of the California Coast Ranges southeast of Fort Bragg. Watershed research has been conducted in the North and South Forks of Caspar Creek since 1961 under a partnership between the U.S. Department of Agriculture Forest Service Pacific Southwest Research Station and the California Department of Forestry and Fire Protection.

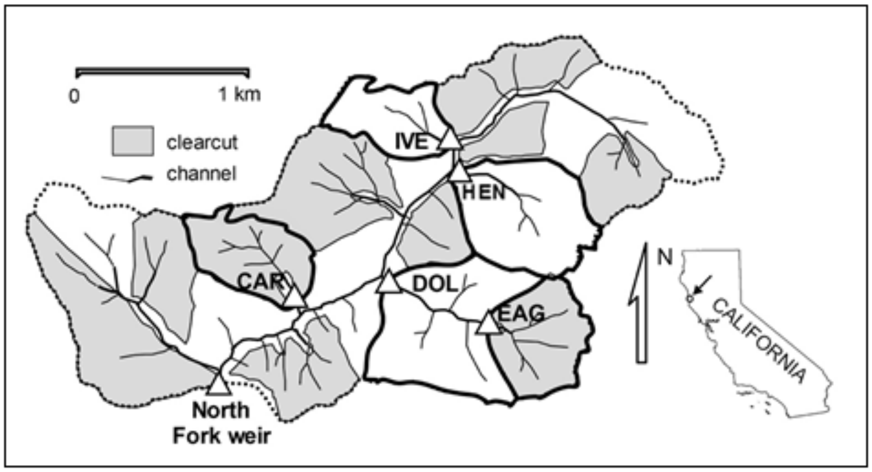

Figure 1—The North Fork Caspar Creek Watershed. Triangles indicate the locations of the gaging stations used for the analysis.

Caspar Creek drains 2,170 ha (5,362 ac), of which 1,958 ha (4,838 ac) are located in Jackson Demonstration State Forest. The 473 ha (1,169 ac) North Fork Caspar Creek watershed is underlain by marine sandstone and shale of late Cretaceous to early Cenozoic age and is incised into Pleistocene marine terraces. Elevations range from 82 to 317 m (270 to 1,040 ft). Soils are 0.5 to 2 m (1.6 to 7 ft) deep and are generally well-drained, with textures ranging from loams and sandy loams to very gravelly loams; most are in hydrologic groups B and C (Rittiman and Thorson 2006). Channel heads are generally present in catchments larger than 1.9 ha (4.7 ac). Approximately 95 percent of the average annual precipitation of 1,190 mm (47 inches) falls between October and April, and many tributaries are intermittent. Nearly half of the incoming precipitation runs off as stream flow, and snow is not hydrologically significant.

Coast redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) are the dominant conifer species present in the Caspar Creek watershed; old-growth trees were logged from the mid-1860s to 1904. Two major watershed experiments have been carried out at Caspar Creek to study the hydrologic effects of second-growth harvesting of coast redwood and Douglas-fir, and a third is currently being implemented. The entire South Fork watershed was selectively logged from 1971 to 1973, and monitoring demonstrated the resulting influences on runoff volumes and peak streamflows. The North Fork experiment was designed to quantify the cumulative effects of clearcutting on suspended sediment, storm runoff volume, and peak flows; logging for the

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[4] Cafferata, P.; Lindsay, D.; Spittler, T.; Wopat, M.; Bundros, G.; Flanagan, S.; Coe, D.; Short, W. Designing watercourse crossings for passage of 100-year flood flows, wood, and sediment (2016). Revised California Forestry Report No. 1. Manuscript in preparation. Sacramento, CA: California Department of Forestry and Fire Protection. 115 p.

second experiment took place from 1989 to 1992, and short-term results were reported by Ziemer (1998) and Lewis et al. (2001).

Methods

Flow Measurements

Large concrete weirs were constructed in 1962 to monitor streamflow and sediment at the North and South Forks of Caspar Creek; flow measurements span the period from 1962 to the present and will continue into the foreseeable future. In 1984, 13 gaging stations were installed in the North Fork watershed, eight of these in small headwater basins (< 40 ha, < 100 ac). Flow monitoring began in water year 1985 (1 Aug 1984 to 31 July 1985). Henry (1998) describes the sub-watersheds, monitoring methods used, and management practices. Flow was measured with wooden Parshall flumes (replaced with fiberglass Montana flumes in 2004), stilling wells, and pressure transducers. The five sub-watersheds having the longest flow records (control sub-watersheds HEN and IVE; clearcut sub-watersheds CAR and EAG, and partially clearcut sub-watershed DOL; fig. 1, table 1) were selected for testing the accuracy of four commonly used flow estimation methods. To provide field-based peak flow values for comparison to estimates, flow frequency analyses were conducted for these five sub-watersheds using the log-Pearson Type III distribution option in PeakFQ, a program available online from the U.S. Geological Survey.

Table 1—The Caspar Creek test sub-watersheds, and empirically derived and modeled estimates of the 10-year return interval (RI) flow in the sub-watersheds

	HEN	IVE	CAR	EAG	DOL
Area [ha (ac)]	39 (96)	21 (52)	26 (64)	27 (67)	77 (190)
Percent clearcut	0	0	96	99	36
Flow record duration (yr)	31	31	31	30	31
Years logged	--	--	1991	1990-91	1990-91
			(all values in cfs)		
10-yr flow	16	7.2	12	12.9	31.7
95% confidence limits	12.9-21.5	5.7-10.0	9.5-16.4	10.6-16.8	25.4-42.6
Flow model predictions, 10-yr flow					
Rational Method (C = 0.2)					
CA culvert practice equation	52	28	34	36	102
Airport drainage equation	29	16	20	21	47
BCMOE equation	24	15	17	18	40
Updated USGS	41	24	28	30	74
Flow transference method					
Standard method	25	15	18	18	46
Direct flow transference	19	10	13	13	37
NRCS WinTR-55	47	27	39	35	95
Tests of modifications					
Rational Method (storm lag)	8	4	6	6	17
Rational Method (burst lag)	10	4	7	7	19

Estimation of Peak Streamflows

We tested four methods that are often used to estimate peak flows associated with crossing design for small forested watersheds in California. These include (1) the Rational Method (using different runoff coefficients and methods for calculating times of concentration), (2) updated USGS Magnitude and Frequency Method equations for the North Coast region (Gotvald et al. 2012), (3) flow transference method (Waananen and Crippen 1977) and a variant of the method (Skaugset and Pyles 1991), and (4) the NRCS WinTR-55 small watershed hydrology program (NRCS 2009).

Rational Method

The Rational Method has been used by engineers for more than 150 years to predict peak runoff rates (Dunne and Leopold 1978). It was developed before long-term flow records were available, and this method remains widely used for estimating design floods in small ungaged watersheds because it requires few data and is easy to use. The Rational Method is often applied in urban watersheds, where most storm flow travels as overland flow on impermeable surfaces, and in small undeveloped watersheds. The method assumes that runoff is generated due to limited infiltration, an assumption that does not hold in many forested watersheds (Skaugset and Pyles 1991). Past studies have found that this method tends to overestimate design floods for non-urban basins (Tolland et al. 1998).

The Rational Method equation for the 100-year flood flow is $Q_{100} = CIA$, where Q_{100} is the predicted peak runoff from a 100-year storm[5] (cfs), C is the runoff coefficient, which may vary by storm size, I is the rainfall intensity for the 100-year storm (in/hr), and A is the drainage area (acres). Flood peak flows of other return intervals (e.g., 5, 10, 25, or 50-year peaks) can also be estimated by using an appropriate rainfall intensity and runoff coefficient.

To determine the rainfall intensity, one must (1) estimate the time of concentration (T_c), the time it takes water falling at the top of the watershed to reach the crossing location, and (2) use rainfall depth-duration-frequency data to identify the 100-yr rainfall for a storm duration equivalent to the T_c. A value for T_c can be estimated using one of more than 30 equations, including the California culvert practice equation (California Division of Highways 1944; modified Kirpich equation), Airport Drainage method (FAA 1970), and the BCMOE (1991) nomograph and equation (Gregori 2003). T_c calculations commonly introduce significant errors in peak flow estimation (Tolland et al. 1998). Selecting the appropriate runoff coefficient (C) is also difficult for small forested watersheds unless the value is locally calibrated, and C can vary with storm size as the relative importance of various flow sources changes (Dunne and Leopold 1978, ODOT 2014). The Rational Method should not be used for watersheds larger than 80 ha (200 ac) (Dunne and Leopold 1978), and is most reliable for those smaller than 40 ha (100 ac). Some authors recommend that it not be used in forested watersheds due to problems in estimating C and T_c (Skaugset and Pyles 1991).

USGS Magnitude and Frequency Method

The updated USGS Magnitude and Frequency Method, which replaces the method described by Waananen and Crippen (1977), is based on a set of empirical equations derived from precipitation and runoff data. Data from 630 stream gaging stations located throughout California were used to derive equations to predict peak flows for 2, 5, 10, 25, 50, 100, 200, and 500-year flow recurrence intervals for six regions of California (Gotvald et al. 2012). The equations were generated from watersheds with drainage areas ranging from approximately 10 ha (25 ac) to over 1,000,000 ha (2,500,000 ac). The 10-yr and 100-yr regression equations for the North Coast region are:

$$Q_{10} = 14.8\, A^{0.880}\, P^{0.696}$$
$$Q_{100} = 48.5\, A^{0.866}\, P^{0.556}$$

where Q_{10} and Q_{100} are the predicted 10-year and 100-year flood flows (cfs), A is the drainage area above the crossing (mi^2), and P is the mean annual precipitation (in). This method is easy to use, mean annual rainfall data are readily available, average standard errors of prediction for each flow recurrence interval in each region are provided, and flow estimates are based on discharge data from numerous, widely distributed locations, including large watersheds subject to rain-on-snow flow events. The primary disadvantage of this method is that it generalizes vast regions of the state, resulting in overestimation in some areas and underestimation in others (Cafferata et al. 2004).

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[5] Runoff data are presented using English units for consistency with common usage by RPFs when designing watercourse crossings (i.e., cfs rather than cms).

Flow Transference Methods

If a gaging station is located on a stream that is hydrologically similar to that at the proposed crossing site, it is possible to adjust the estimate for a peak flow of a given recurrence interval at the gaged site to provide an estimate for the ungaged site simply on the basis of the drainage areas. For 100-year flow estimation (Forest Service Stream-Simulation Working Group 2008, Waananen and Crippen 1977),

$$Q_{100u} = Q_{100g}\,(A_u/A_g)^b$$

where Q_{100u} and Q_{100g} are the 100-year flows (cfs) at the ungaged and gaged sites, respectively; A_u and A_g are the drainage areas at those sites (mi^2), and *b* is the exponent for drainage area from the appropriate USGS Magnitude and Frequency equation (e.g., 0.866 for the 100-year flow in the North Coast Region). Flows of other return intervals and regions are calculated using their corresponding *b*-values, which are tabulated by Waananen and Crippen (1977). The gaging station records should span at least 20 years, and the peak flow at the gaged station must be estimated for the desired return interval (e.g., 10, 25, 50, 100-year). This method is most reliable where the drainage area of the ungaged site is between 50 and 150 percent that of the gaged site (Sumioka et al. 1998). When adequate records are available from a nearby gaging station, this method is expected to provide more reliable results than either the more general USGS Magnitude and Frequency Method or the Rational Method (Cafferata et al. 2004).

An alternative flow transference method can be used if the gaged and ungaged watersheds are relatively small (e.g., < 1000 ha or <~ 2,500 ac), are in close proximity, are hydrologically similar, and are within approximately one order of magnitude in size. The Direct Flow Transference Method (Skaugset and Pyles 1991) simply adjusts the value at the gaged station by the ratio of watershed areas:

$$Q_{100u} = Q_{100g}\,(A_u/A_g)$$

NRCS WinTR-55 Small Watershed Hydrology Program

Several computer programs are available that use the unit hydrograph approach to estimate flood flows for more complicated situations. One of the most widely used is the NRCS WinTR-55 program, which was developed for estimating runoff from small agricultural catchments and watersheds with other kinds of land uses. NRCS (2009) provides detailed information on the TR-55 program, which was constructed using the SCS curve number (CN) methodology. Curve numbers are defined as an "empirical rating of the hydrologic performance of a large number of soils and vegetative covers." They range from 0 to 100, and a spatially weighted average CN provides an index of storm runoff generation capacity. The maximum area for this method is 6,500 ha (~16,000 ac), and up to 10 sub-watersheds may be considered.

The NRCS WinTR-55 program is not commonly used for estimating design flows at forest road crossings, but it is often used to assess the potential hydrologic effects of timberland conversion projects (e.g., vineyard conversions) and has been accepted for routine use by some regulatory agencies. It is particularly useful when streamflow is regulated by upstream detention ponds or reservoirs. The main disadvantage for designing forest stream crossings is that curve numbers are not well defined for forested areas, and this often results in problematic estimates at such sites (Fedora 1987, Skaugset and Pyles 1991). Despite these problems, unit hydrograph analysis using SCS curve numbers is generally thought to provide reasonable estimates for predicting a relative change in peak flows due to land-use modification.

Applying Peak Flow Estimation Methods to the Test Watersheds

Each peak flow estimation method requires measurement or estimation of the values of various parameters. Several approaches are available for estimating the *C*-value for use in the Rational Method. A value of 0.3 or higher has often been recommended for use in woodland areas on loam or clay soils (Cafferata et al. 2004, Dunne and Leopold 1978), and prior applications of the method have often used a value of at least 0.3 at similar sites. However, Cafferata et al. (2004) and Cafferata and Reid (2013) demonstrated that the 0.3 value produces overestimates of peak flows in the Caspar Creek watershed for both for 10-yr and 100-yr calculations. Therefore, we adopted the recommendations of ODOT (2014) for woodlands and forests and used a value of 0.2 for a 10-yr storm and 0.25 for a 100-yr storm; we then compare these results with those obtained using a value of 0.3 for both 10-yr and 100-yr flows. T_c was calculated for each of the five sub-watersheds using the California culvert practice, Airport Drainage, and BCMOE equations. Required information, including elevation difference, average channel gradient, and flow distance, was determined using a digital topographic map. Rainfall depth-duration-frequency data were obtained from the NOAA website, "Atlas 14 Point Precipitation Frequency Estimates for California."

The USGS Magnitude and Frequency Method requires an estimate of the mean annual precipitation, for which we used the value of 1190 mm (47 in) as indicated by the 1961-1997 record (Henry 1998). Application of flow transference methods makes use of flow frequency information from a long-term stream gage. We used the 53-year record from the North Fork Caspar Creek gage, located downstream of the five test sub-watersheds (fig. 1). For the NRCS WinTR-55 method, weighted curve numbers for sub-watersheds were determined by estimating the percent of the basin drainage area in each hydrologic group (e.g., B, C) using NRCS soil series data. The NOAA atlas website was used to obtain rainfall depth-duration frequency data for a 24-hour duration for a variety of return periods.

We used 10-year flows for the primary analysis because the largest flows in some of these sub-watersheds had return intervals of less than 25 years, and the length of the measured record is not sufficient to allow accurate estimates of the 100-year flows. However, we expect that the relative reliability of methods for predicting 10-year peak flows is likely to also characterize their reliability for estimating 100-year events (Cafferata et al. 2004), and we tested this assumption by carrying out calculations also for the less-well-defined 100-year flows.

Results

The flood frequency distribution calculated from HEN gaging records using the USGS PeakFQ program shows only minor variation about the best fit model and is typical of those constructed for the other four sub-watersheds (fig. 2). We then compared the values predicted by each of the flow estimation methods to the 10-year flow calculated from gaging station records for each of the five test sub-watersheds (table 1).

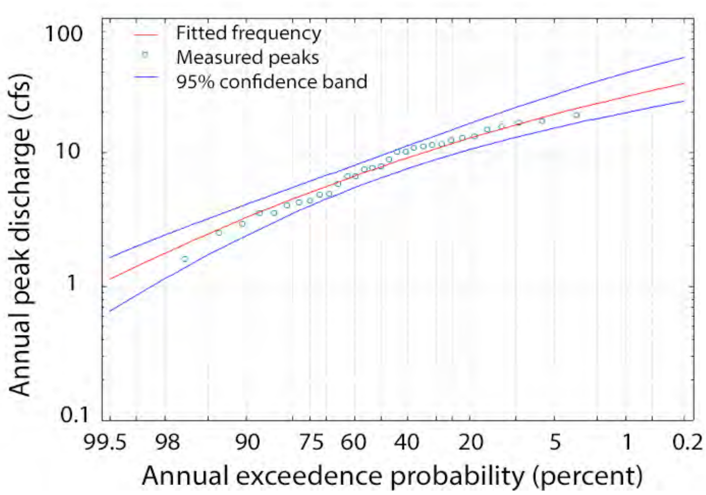

Figure 2—Flood frequency curve for sub-watershed HEN.

Each of the four flow estimation methods tested over-predict the 10-year event for the five test sub-watersheds (table 1, fig. 3A). Departures from the flow frequency analysis results were highest (mean: 220 percent) for the Rational Method using the California culvert practice equation to determine the T_c, while the direct flow transference method provided the lowest overestimate (mean: 17 percent).

The 31-year duration of flow records is too short for a highly reliable estimate of 100-year flows, but calculation of those flows remains useful in order to determine whether the patterns of accuracy established for the 10-year flows are likely to hold also for the larger flows. Results indicate that the patterns of deviation are indeed similar (fig. 3B). In this case, too, using the California culvert practice equation with the Rational Method—this time with C = 0.25, as recommended by ODOT (2014) for 100-yr flows—provided the least reliable estimates, while the direct flow transference method provided the lowest overestimate (9 percent).

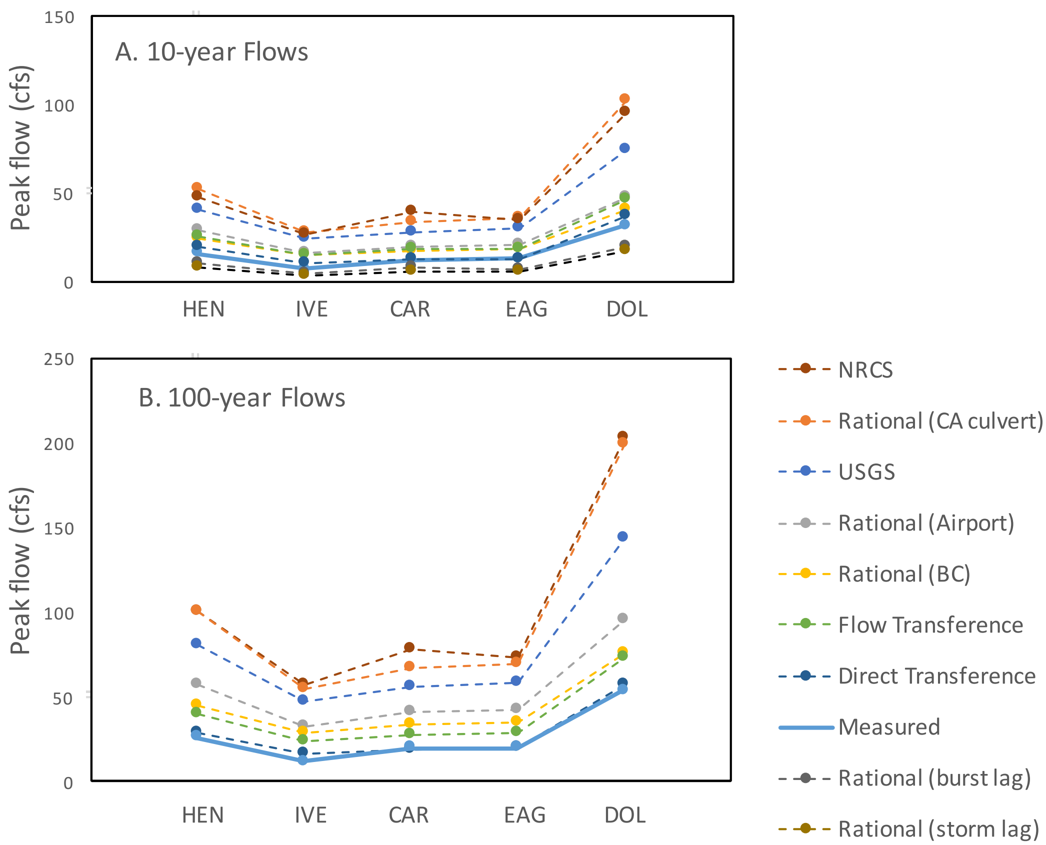

Figure 3—Predictions of the (A) 10-year and (B) 100-year discharge for the five gaging stations.

Discussion

Comparison with Results From Elsewhere

Results of this study are generally similar to those reported for other west coast studies that compared peak flow prediction methods or T_c equation results to measured storm peaks. Fedora (1987) found that the SCS curve number methodology over-predicted peak discharge by a factor of two in the Alsea watershed located in the Oregon Coast Range. Gregori (2003), using data from the H.J. Andrews Experimental Forest in the Oregon Cascades, and Loukas and Quick (1996), working with data from the Carnation Creek watershed in British Columbia, found that standard T_c equations considerably underestimated watershed response time, which would result in overestimation of peak flows. Cafferata et al. (n.d.) reported that the Rational Method using the California culvert practice equation for T_c overestimated the 100-year flow by 130 percent for a headwater tributary in the Teakettle Experimental Forest in the Sierra Nevada. The Rational Method using the Airport Drainage and BCMOE equations for T_c, the USGS Magnitude and Frequency Method, and the flow transference method produced estimates that were within 20 percent of the estimated 100-year discharge at that site.

Comparing the Models

In the present case, the Rational Method, using the California culvert practice equation for T_c and a *C*-value of 0.2 for 10-yr flows, produced results that were the most divergent from the values derived from the flow frequency analysis. This outcome in part reflects the difficulty of defining appropriate values for *C* and T_c in a region where flow generation processes are not those for which the method was developed. T_c, in particular, has a clear physical meaning for this application only in watersheds dominated by overland flow. In contrast, subsurface flow dominates at Caspar Creek, with soil matrix flow draining into a network of soil macropores. The first channelized flow is thus through soil pipes of unknown extent. Consequently, neither the typical flow path nor the portion of the watershed that directly contributes flow to a particular storm's runoff can be reliably defined. It is thus useful to explore alternative approaches to defining Tc and C to evaluate whether modifications to the approach might be effective in such settings.

To determine whether a more empirically-based index of hydrologic response time might improve the performance of the Rational Method under these conditions, we calculated the storm centroid lag to peak (fig. 4) from hydrographs and hyetographs for a 10-yr event in each sub-watershed and used these values in place of calculated T_c values to identify the relevant rainfall intensity, again using C = 0.2. The resulting estimated flows consistently underestimated the 10-yr peak flows (fig. 3A, table 1).

A second set of calculations, this time using the centroid lag to peak from just the within-storm rain period that generated the peak (the "burst lag" in fig. 4), also consistently underestimated observed values (fig. 3A, table 1). These modifications would lead to valid estimates only if the value for *C* is about twice that expected. In the case of sub-watershed HEN, the response times for the storm centroid and burst centroid lags to peak were 366 and 269 minutes, respectively.

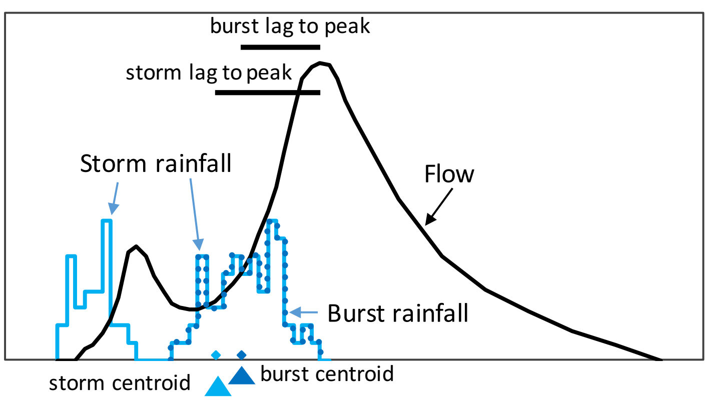

Figure 4—Hypothetical hydrograph showing definition of terms for lag calculation.

Definition of an appropriate *C*-value is also problematic. Forestland *C*-values recommended by various sources span the range of 0.1 to 0.6, and because *C* is a simple coefficient, the resulting estimated peak flows would differ by up to a factor of 6. In the case of coastal forestlands, past recommendations have suggested using values no lower than 0.3. For the present application, use of C = 0.3 appreciably increased the overestimates. Cafferata and Reid (2013) used the Caspar Creek data to attempt to identify an appropriate *C*-value for this area. For that application, T_c was calculated using the Airport Drainage equation (T_c = 34 min for sub-watershed HEN), and an appropriate *C* value was back-calculated from the observed 10-yr peak. In effect, inaccuracies in both *C* and T_c were collapsed into a single variable under the assumption that these inaccuracies would be relatively uniform for conditions across the area of interest. The resulting value (C = 0.13) was tested by comparing predicted and observed 10-yr flows in a variety of nearby watersheds. Results showed reasonable agreement for watersheds smaller than 80 ha (200 ac). This result suggests that the Rational Method might become a useful approach in an area if sufficient data are available for calibration, but the need for local data to a large extent counters the attraction of the original method.

The USGS and flow transference methods are similar to one another in that both are based on calibrations—the first at a regional scale and the second more locally. The USGS method was less accurate than either of the flow transference methods tested, but it has the advantage of not requiring local data for calibration, and it can be applied to larger watersheds. At Caspar Creek, the flow transference methods provided the most reliable estimates, but application at this site is not typical because the data used to calibrate the model were from a stream gage in the same watershed as the sub-watersheds studied. Cafferata and Reid (2013) tested the transference methods for a more typical case, using data from the Noyo River USGS gage 6 km (4 mi) from the watershed, and found that the methods performed similarly to the USGS Magnitude and Frequency Method and the Rational Method using the Airport Drainage equation to calculate T_c. Finally, the NRCS WinTR-55 approach did not perform well at Caspar Creek; as is the case with the Rational Method, it functions better in watersheds where overland flow is an important source of runoff.

Differences Between Sub-watersheds

Examination of the differences in model performance between individual sub-watersheds showed that the models performed consistently less well for the IVE watershed (fig. 5), suggesting that the hydrologic response at IVE differs from those at the other sites tested. This difference is also supported by field observations: IVE hydrographs show larger lags to peak and more protracted peaks than other sites, and the catchment also supports perennial flow, a rarity for watersheds of this size (21 ha, 52 ac) in this area.

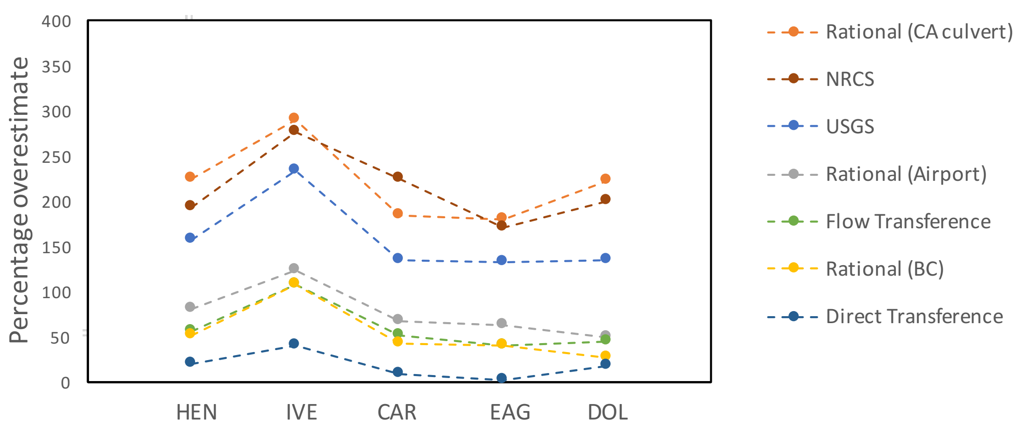

Figure 5—Percent over-estimation for 10-yr flows in the test sub-watersheds.

Little information exists on whether peak flow changes associated with forest management are large enough to affect crossing design. Previous studies demonstrated increased peak flows after clearcutting at Caspar Creek (e.g., Lewis et al. 2001, Ziemer 1998). The current study employed data for sub-watersheds CAR, EAG, and DOL that spanned the period before logging, immediately following logging, and during the hydrologic recovery of the watersheds. Periods of uniform conditions could not be isolated for analysis due to the need for a lengthy record in order to adequately define 10-yr return-interval flows, and because a trend toward recovery begins soon after logging is completed. Furthermore, gaging records used to calibrate the USGS and flow transference methods also reflect partially logged watersheds. It is possible that the generally lower overestimates obtained by these methods for the clearcut and partially clearcut sub-watersheds (fig. 5) may simply reflect an increase in peak flow in these basins relative to the control sub-watersheds HEN and IVE, though data are insufficient to test this possibility. In any case, crossing designs should take into account potential changes in peak flows that might take place due to land-use activities upstream of the crossing.

Implications for Crossing Design

Each of the flow prediction methods tested has different data requirements. The flow transference methods, while producing the best results at Caspar Creek, are often limited by the availability of gaging data from nearby hydrologically similar watersheds. In contrast, the USGS, NRCS, and Rational Methods all require data that are now readily available from digital topographic maps and internet sites. Choice of the most effective model to use for a particular application thus depends in part on the kinds of information available. For any application, it is advantageous to apply several of the methods in order to evaluate the likely uncertainty associated with any one method’s results. Office-generated results always need to be evaluated in the light of field observations of factors such as bankfull channel capacity, active channel width, and crossing performance at nearby sites after large flood events.

In the coast redwood region, large flows alone generally are not the primary cause of watercourse crossing failures (Flanagan 2004). For storms with return intervals of < 12 yr, some combination of woody debris and sediment deposition accounted for 86 percent of the crossing failures inventoried across a range of site conditions in northwestern California, while hydraulic exceedance and debris torrents produced 12 and 2 percent, respectively (S. Flanagan, BLM, Arcata, unpublished data; n = 57). Similarly, Furniss et al. (1998) found that only 9 percent of failed crossings in the Pacific Northwest and northern California resulted from hydraulic exceedance. The California Forest Practice Rules thus require that crossings be designed to allow adequate passage not just of water, but also of wood and sediment.

Unfortunately, analytical methods analogous to those for peak flow prediction are not available to aid in sizing culverts for wood and sediment passage. Furniss et al. (1998) outline several approaches that can help to reduce failure risk: (1) ensuring that the pipe diameter (D) is large enough that headwater depth (HW) remains well below the top of the pipe ($HW/D \leq 0.67$ preferred), (2) installing culverts of similar width as the active channel, (3) installing culverts at the same gradient as the natural channel, (4) aligning culverts so that they are parallel to the natural channel, and (5) eliminating wide areas near pipe inlets. Additionally, the risk of culvert failure can be reduced by installing a single large pipe rather than multiple pipe barrels, placing flared metal end sections at culvert inlets, using mitered pipe inlets, and installing trash racks where winter maintenance is possible. Flanagan (2004) noted that if a culvert is sized for wood passage (i.e., the pipe width is approximately equal to the active channel width), hydraulic capacity is generally adequate for the 100-year flow.

In many situations, the best approach for reducing the risk of crossing failure is to not install a culvert. Use of rock fords, rock-armored crossings, bridges, and open-bottom arch installations has become much more common in the past 15 years in the redwood region. Site-specific conditions that may lead to preference for these types of crossings include winter maintenance issues, landslide-prone terrain, the presence of large amounts of mobile wood, and fish passage requirements. These types of crossings must also be sized for 100-year flows but are less sensitive to both flow prediction errors and wood- or sediment-induced failure than are culverts. The most failure-resistant design, however, is not to use permanent structures, but to instead install temporary crossings that are removed prior to winter.

Conclusions

Numerous approaches are available to RPFs in California to estimate 100-year flood flows for crossing design. The four commonly used methods we tested at Caspar Creek produced widely varying results. The Rational Method, often used for small watersheds, was shown to be capable of producing reasonable flow estimates if appropriate C and T_c factors are used. We do not recommend using the California culvert practice equation to calculate T_c; both the Airport Drainage and BCMOE methods produced more realistic values. The flow transference methods that used data from a nearby stream gage provided the most accurate estimates. The NRCS WinTR-55 method did not produce accurate estimates for the 10-year peak flows. The USGS Magnitude and Frequency Method equations produced results better than those from the NRCS method, but considerably poorer than those of the flow transference methods. Future flow data from Caspar Creek will allow more rigorous testing of estimates for larger flows (> 10 yr RI).

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