Design Storms

In order to use the hydrologic model for analysis of flooding conditions in the Easkoot Creek basin, it is necessary to quantify the range of flows associated with various return intervals. These flows will then be used as input to the hydraulic model, which will in turn be used to quantify the phenomena of interest during flooding events. The desired flows are derived by running the calibrated model with input design storms that incorporate the total rainfall depth associated with the various return intervals. In that process, spatial variations over the model domain (mainly due to topography) must be accounted for, and both the duration of the design storm and the temporal distribution of the rainfall over that period must be specified and should be appropriate to the watershed. A further issue in our case arises from the fact that an important parameter for the hydrologic model, the initial abstraction I_a (i.e. antecedent soil moisture conditioned by storm events occurring prior to a hypothetical design storm), was not constant over all the calibration storms, so the appropriate set of values for use with the design storms needs to be determined.

The design rainfall depths used were derived from *NOAA Atlas 14 (Volume 6, Version 2.0)* that succeeded the previous NOAA Atlas for California in 2011, for which data are available from the convenient online *Precipitation Frequency Data Server* (http://hdsc.nws.noaa.gov/hdsc/pfds/). Atlas 14 is based on a considerably larger number of long-term stations than its predecessor Atlas 2, and its usefulness for work in Marin County was enhanced by the inclusion of data for a number of North Bay locations which were made available by Marin County staff. Data were obtained from the Precipitation Frequency Data Server for 24 hour duration storms with return intervals of 2, 10 and 100 years, which was comparable to the historical storms used to calibrate the hydrologic model.

A comparison of the range of values in the NOAA data over the Easkoot Creek watershed showed that, although the data are somewhat coarse, they do capture the spatial variation convincingly. A comparison between the Easkoot Creek gauge and the RAWS daily rainfall gauge on Middle Peak (Mt. Tamalpais) shows that Middle Peak gets about 1.5 times as much rainfall as Easkoot, according to the Atlas 14 data, which is quite consistent with the measured data for these two stations during the January 2008 event and the December 2004 event, the only two of our calibration storms for which this explicit comparison can be made. The NOAA raster data for the Easkoot Creek watershed were downloaded and re-sampled to produce data at a much finer resolution, and mean values of rainfall depth were computed for each model sub-basin.

The temporal distribution of design rainfall amounts over the 24-hour storm duration required careful consideration. In Appendix A.6, the NOAA Atlas includes a range of temporal distribution curves for several durations, including the 24-hour duration we used, for the various climate regions in California. We considered using one of these, but we found that the variation in rainfall intensity that was observed during calibration storms was much greater than that portrayed in the NOAA Atlas. There appears to be a smoothing effect in the calculation of the median distributions in the NOAA Atlas. Rainfall intensity data for all three of our calibration storms had ratios of maximum-to-mean intensity were around 5.0. For a small, steep watershed such as Easkoot Creek where time of concentration is relatively short, peak rainfall intensity is expected to have a substantial effect on peak stream discharge. Consequently, we used the ratio of maximum-to-mean rainfall intensity as a criterion in selecting an appropriate design storm.

The SCS IA 24-hour temporal distribution of rainfall intensity was found to have a ratio of maximum/mean intensity of 5.5, so this distribution was initially adopted as being more consistent with our observed storms. When evaluated in the HMS model however, we found that the shapes of the resulting hydrographs using the SCS 1A rainfall distribution were not very realistic when compared to the historical storms at gauge EK (Figure 11). In particular, the simulated hydrographs have steeper rising limbs and much more gradual recession limbs compared to the gauged hydrographs.

To investigate the relationship between rainfall intensity and runoff hydrographs further, we examined the intensities of the three historical storms in by computing intensities over a variety of durations and developing a balanced storm hyetograph by stacking the historical intensities for various durations around the highest intensity which was placed in the middle of the storm. We also followed a similar procedure using the NOAA Atlas 14 rainfall depths for various durations to develop a balanced storm hyetograph. The rainfall distributions are very similar for the two balanced storm approaches (Figure 12). Due to the fact that the historical rainfall intensities were calculated from 15-minute interval data rather than from raw tipping bucket data and the fact that it is unknown how representative these three events may be, we selected the balanced storm hyetograph that utilized the NOAA Atlas 14 rainfall depths and re-evaluated the design storms with the HMS model.

Using the balanced storm approach, the resulting hydrograph shapes are much more consistent with the historical events (Figure 13). Given this improved agreement with the historical storms and the consistency between the balanced storm hyetographs developed from the historical data and from the NOAA Atlas 14 data, we believe that the revised HMS results provide the most representative design storm hydrograph possible given the available data.

To resolve the issue of the appropriate antecedent moisture condition (represented by I_a) to be used with the design storms, we first ran each of the three design storms as a set of three cases with a *high*, *low* or *medium* assumption regarding the value of I_a. The definitions of each of these cases are shown in Table 8. The high and low values come from different calibrated storms, and the medium value is the default SCS value defined as 0.2S, where S is the maximum potential abstraction and is a function of the curve number.

In order to validate the HMS predictions and help decide which antecedent moisture condition is most appropriate for developing our design storm hydrographs, we utilized three additional flood frequency analysis techniques and compared the results to the HMS results. The first approach was to apply the USGS's regional regression equations using the NSS (National Streamflow Statistics) Program[16]. The second approach was to analyze the 8-year flow record at gauge site EK using the PKFQ Program, which is based on the methods of USGS Bulletin 17B[17] to calculate a flood frequency distribution. It is important to note that the EK gauge record is not of sufficient length to make the results highly reliable (a 10-year record is the recommended minimum for the USGS procedure; we used an 8-year record). Nevertheless we believe it is still useful for these purposes. The third method was to scale the results of the flood frequency analyses for Redwood Creek (National Park Service, 2010) and Corte Madera Creek (Stetson, 2010) on the basis of drainage area so that they predict peak flow for a basin with the drainage area of Easkoot Creek.

[16] http://water.usgs.gov/osw/programs/nss
[17] http://water.usgs.gov/software/PeakFQ

Table C8 Definitions of Abstraction/Antecedent Moisture Cases

Abstraction	*Typical I_a value (Sub-basin G)*	*Source*
High Abstraction, (Low Antecedent Moisture)	0.92	Calibrated model for December 04, January 08
Medium Abstraction	0.61	Default value for SCS method
Low Abstraction, (High Antecedent Moisture)	0.18	Calibrated model for December 05

The HMS results fall within the error bounds of the NSS and PKFQ results with the exception of the 2-yr event for the low and high antecedent moisture assumption which fall below and above the error bounds respectively (Figure 14). The HMS results are generally lower than the Redwood Creek and Corte Madera Creek results, particularly with the medium and low antecedent moisture assumptions, but they converge for the 100-year event with either high or medium antecedent moisture assumptions (Figure 14).

Perspective on the magnitude of peak flows in relation to individual storm events may be gained by reviewing the recurrence interval assigned to the December 2005 event for the studies of Corte Madera Creek and Redwood Creek. The Corte Madera Creek study assigns this event a 100-yr recurrence interval whereas the Redwood Creek study assigns it a 2.5-yr recurrence interval. Large differences in rainfall between the two sites are not unexpected given potentially complex orographic effects in the vicinity of Mt. Tamalpais. Based on mean annual rainfall distributions, the Corte Madera Creek watershed north and east of Mt. Tamalpais appears to receive additional rainfall relative to either Redwood Creek or Easkoot Creek (Figure 15). It is nevertheless surprising that such a large difference in recurrence interval is reported for the same storm event for two watersheds separated by less than 10 miles. Anecdotal accounts provided by residents in the Easkoot watershed regarding the severity of the December 2005 event suggest that it was substantially greater than a 2.5-yr event as is reported for Redwood Creek. An analysis of this storm event by USGS reported that most gauges in the North Bay region recorded peak flows in the 10 to 25 year recurrence interval range.[18]

For reference, our analyses suggest that the December 2005 event (peak discharge of about 175 cubic feet per second (cfs)) was between a 7- and 8-year recurrence interval event based on the HMS results for the medium antecedent moisture assumption scenario (Figure 14). This is reasonably consistent with USGS analyses of that storm event in northern California, as well as what was reported by residents in the Easkoot Creek watershed. We do not have an explanation for the apparently anomalous (low) flow recurrence interval for the event in Redwood Creek (2.5-yr).

We selected the HMS results using the medium antecedent moisture scenario for our design storm (middle black diamonds in Figure 14; Table 9). Although this scenario produces peak flow estimates that are substantially less than predictions for Easkoot Creek scaled from flood frequency curves for Redwood Creek and Corte Madera Creek, we believe they represent the best estimate due to the fact

[18] Parrett, Charles, and Hunrichs, R.A., 2006, Storms and flooding in California in December 2005 and January 2006—A preliminary assessment: U.S. Geological Survey Open-File Report 2006–1182, 8 p.

that they fall within the error bounds of both the NSS and PKFQ results for all recurrence intervals, and they converge for the 100-yr recurrence interval peak flow.

Given the uncertainties inherent in estimating the design storm magnitudes and hydrographs, we recommend utilizing the December 2005 event (the flood of record in available gauging records for Easkoot Creek) as the primary basis for evaluating flood control alternatives with the hydraulic model and relying on the design storms as a secondary means of evaluation. We believe that by considering both the documented 2005 event (estimated 8-year recurrence interval) and a simulated 100-year event, we are able to provide a balanced consideration of flood potential. This approach considers both a directly measured rainfall and runoff event in Easkoot Creek that produced substantial flooding in Stinson Beach and an empirically-derived hypothetical rainstorm to simulate a 100-year recurrence interval flood event.

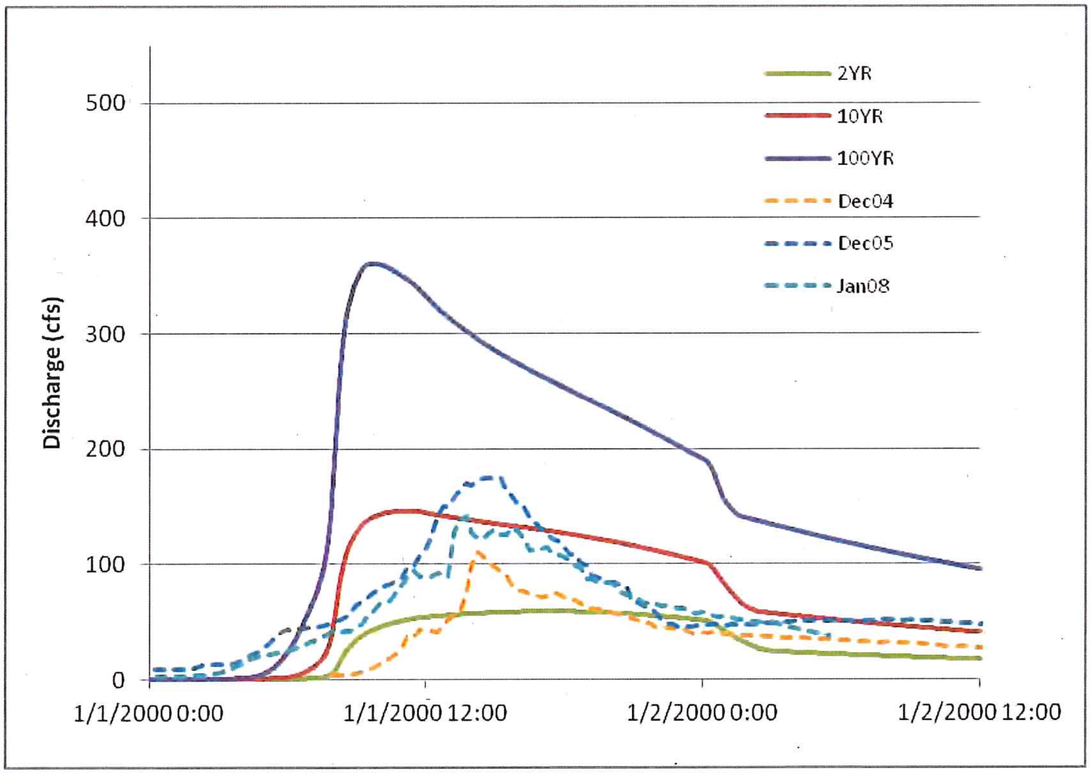

Figure C11 Comparison of gauged historical storms and preliminary hydrographs.

(Produced from the HMS model using an SCS 1A rainfall distribution.)

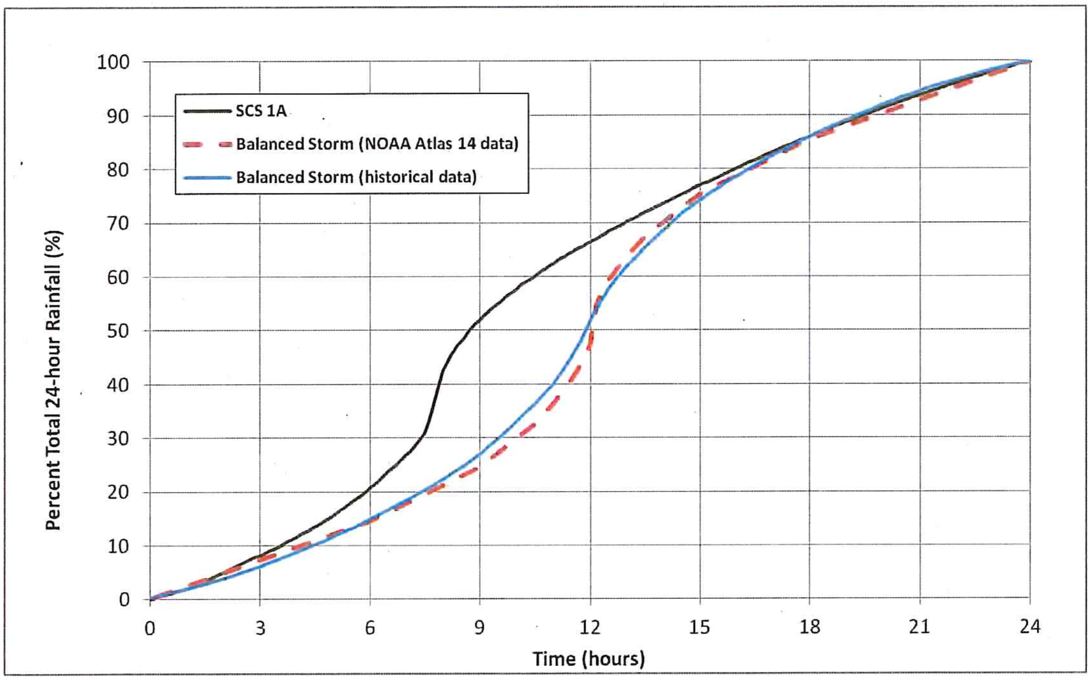

Figure C12 Comparison of rainfall distributions using SCS 1A.

(A balanced storm approach derived from historical rainfall data, and a balanced storm approach derived from NOAA Atlas 14 depths for various durations.)

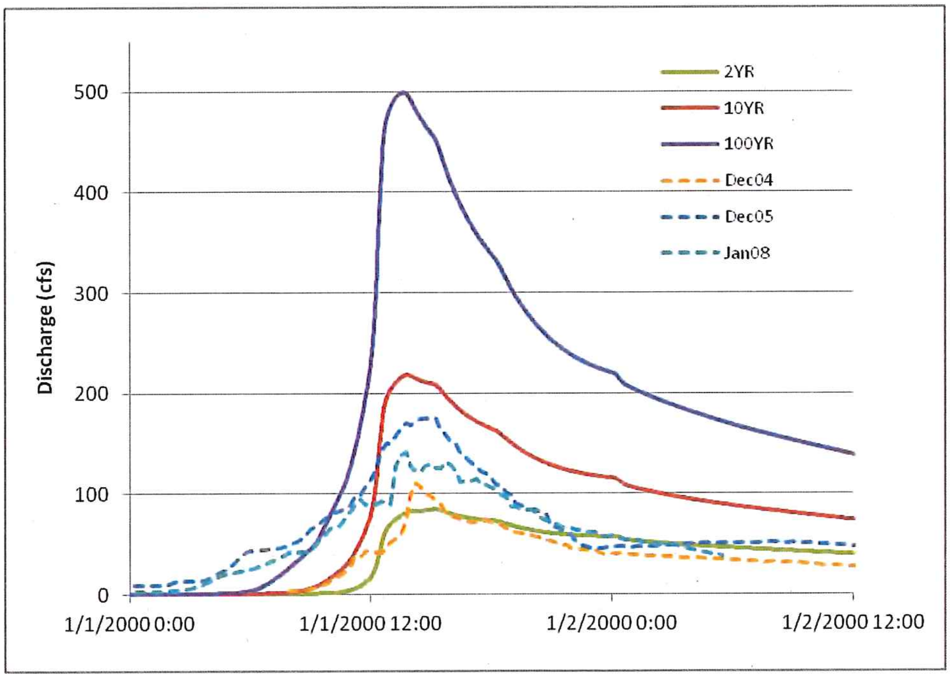

Figure C13 Comparison of gauged historical storms and final hydrographs.

(Produced from the HMS model using a balanced storm approach based on NOAA Atlas 14 depths for various durations.)

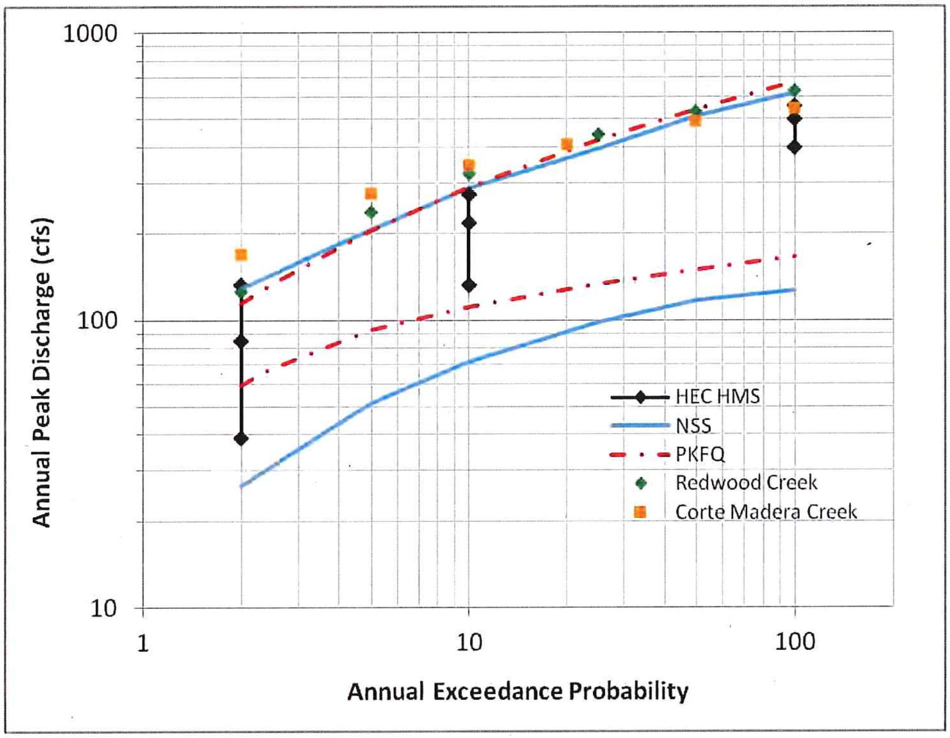

Figure C14 Flood frequency analysis for Easkoot Creek.

(Comparing the HMS model results for low, medium, and high I_a assumptions (black diamonds), with results obtained from the NSS and PKFQ analyses (shown as upper and lower bound estimates) and those obtained from studies of nearby watersheds adjusted for Easkoot Creek's drainage area.)

Table C9 Design storm peak flow magnitudes for Easkoot Creek at entrance bridge to NPS Stinson Beach parking lots.

Recurrence Interval (yrs)	*Annual Probability of Occurrence*	*Peak Discharge (cubic feet per second (cfs))*
2	0.5	85
10	0.1	218
100	0.01	499

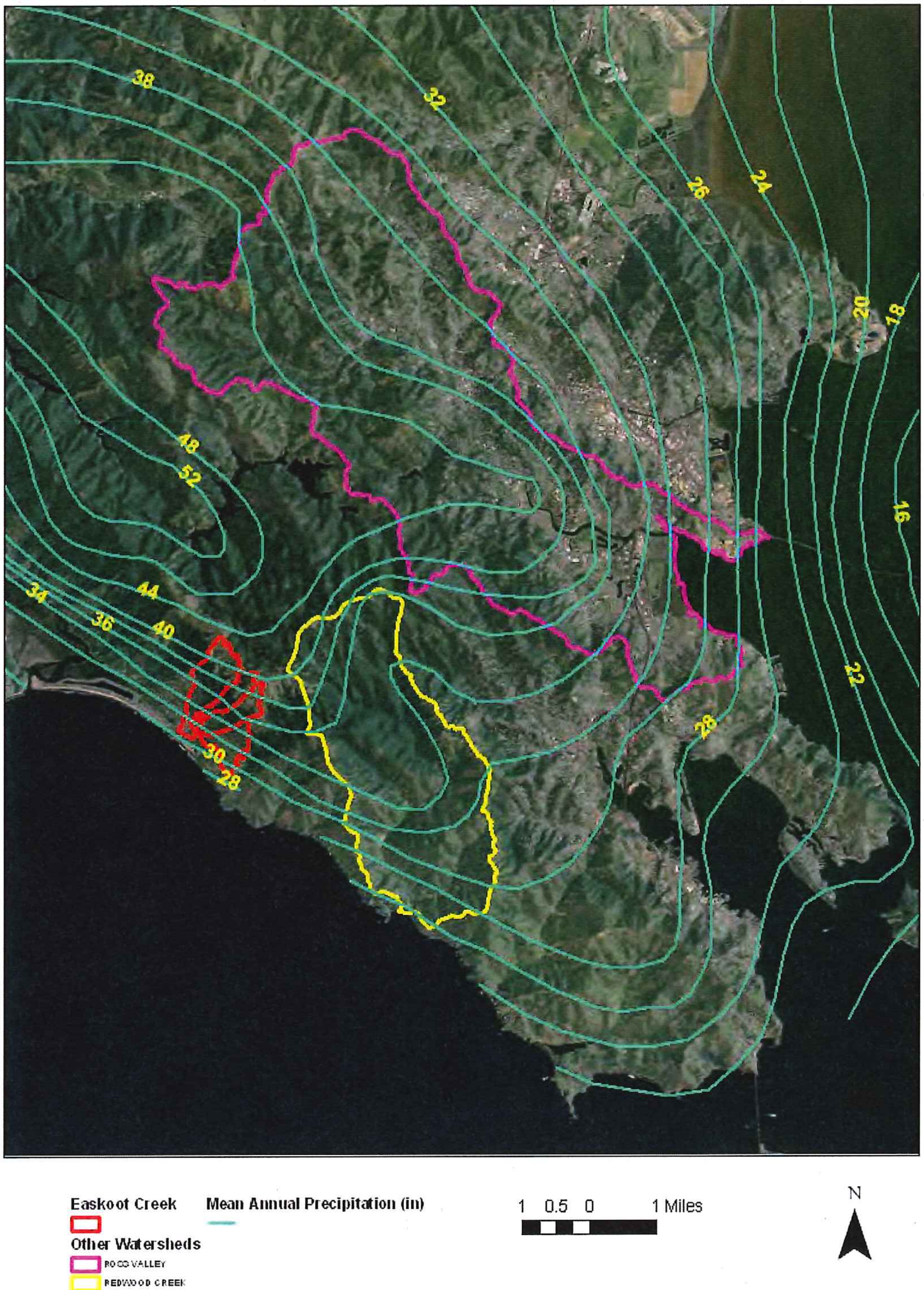

Figure C15 Isohyetal map of southern Marin County.

Note that Ross Valley watershed (shown in pink) is described as Corte Madera Creek watershed in the text.