When ENSO Reigns, it Pours: Climate Forecasts in Flood Planning

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Abstract

Recent scientific and technical advances have increased the potential use of longterm seasonal climate forecasts for improving water resource management. This paper examines the role that forecasts, in particular those based on the El Nino-Southern Oscillation (ENSO) cycle, can play in flood planning in the Pacific Northwest. While strong evidence of an association between ENSO signals and flooding in the region exists, this association is open to more than one interpretation depending on: a) the metric used to test the strength of the association; b) the definition of critical flood events; c) site-specific features of watersheds; and d) the characteristics of flood management institutions. A better understanding and appreciation of such ambiguities, both institutional and statistical, is needed to facilitate the use of climate forecast information for flood planning and response.

Key Words: Flooding, Climate, ENSO, Water Resources Planning, Water Policy, Water Management

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1. Introduction

Despite the evolution of hazard management practices during the last 50 years, Americans remain vulnerable to floods. Fatalities from these disasters have remained relatively constant, with an average of 70 or more in each of the last five decades (Mileti 1999, p. 72). In addition, oft-cited estimates from the U.S. National Weather Service indicate that flood-related property damages have increased, exceeding \$3.5 billion per year in real terms (1997 dollars) in each of the last five decades and climbing to \$5.5 billion per year during the 1990s (U.S. National Weather Service 2000a; U.S. National Weather Service 2000b). Moreover, these figures do not take into account indirect impacts such as lost tax revenues, loss of income, and social disruption—including the spread of disease—which are not well documented.

Popular media coverage has attributed the upward trend in flood damages to a higher frequency or intensity of extreme events, but this view has been challenged by evidence that societal factors (such as an aging infrastructure, higher population densities, and changing development patterns from growing wealth) are driving the increase (Chagnon et al. 2000; Pielke and Downton 2000). In either case, in the face of escalating damages, commentators have suggested that greater reliance on sophisticated climatological and hydrological information in pre-flood mitigation efforts could reduce our vulnerability to floods. Recent technical and scientific advances have deepened our understanding of the connections between changes in large-scale atmospheric patterns and physical and social impacts experienced across the globe. In addition, not only are long lead-time climate forecasts becoming more accurate, they also are increasingly well disseminated. The Climate Prediction Center, for example, issues long-lead forecasts of precipitation and temperature anomalies online through its *Climate Diagnostic Bulletin*.

The purpose of this paper is to examine some of the evidence that undergirds the use of climate forecasts for flood planning, and highlight some of the difficulties encountered when interpreting this evidence. Our objective is to demonstrate the potential utility of climate forecasts in flood planning and to identify the technical and institutional limitations that impede the fuller utilization of forecasts for this purpose.

Our premise is that the utilization of forecast information in flood planning is not straightforward. For climate forecasts to be of value, the timing of the forecast and, more importantly, the content of the information must be both relevant and topical to help flood managers act to reduce risks from flooding. Several studies have examined how climate forecast information has been used by farmers (Mjelde and Hill 1999; Mjelde, Thompson, and Nixon 1996; Roncoli, Ingram, and Kirshen 2000; Tibbetts 1996), water resource managers, and hydrosystem operators (Callahan, Miles, and Fluharty 1999; Georgakakos et al. 1998; Pulwarty and Redmond 1997; Pulwarty and Melis 2001). These studies show that the potential usefulness of climate forecasts depends upon what a recent report by the National Research Council (1999) has called the recipients' "decision situation." Clearly, the value of these forecasts, in part, will depend upon the ability of end users to incorporate new information into organizational routines and to act promptly to change organizational behavior if need be. What has been less studied, particularly in the context of flooding, is how this organizational response to climate forecasts information may be constrained by the ambiguity of that forecast information.

By way of overview, we first provide background on the general relationships between climate disturbances such as an El Niño and river flows that have been observed in the United States, as well as briefly mention several examples where flood planners have successfully utilized seasonal climate forecasts. We then present evidence of an association between specific climate signals and flood indicators in several basins in the Pacific Northwest, a region where the association between seasonal climate signals and runoff appears particularly strong. After this, we extensively discuss major ambiguities in this evidence. We conclude by highlighting several areas where a better understanding of the process of using climate forecast information might facilitate flood planning and response.

2. Background

Several investigations in the last decade (for example, Cayan and Redmond 1994; Gershunov and Barnett 1998; Kiladis and Diaz 1989; Pielke and Landsea 1999; Ropelewski and Halpert 1996) have examined the relationships between large-scale atmospheric patterns and a range of weather anomalies and surface runoff characteristics. Despite omnipresent difficulties in obtaining and interpreting a consistent long time series of river discharges, and in accounting for possible shifts in climate regimes (Dettinger et al. 2000; Trenberth and Hoar 1996), researchers have found strong associations between surface hydrology and climate anomalies—including those that occur at the time scale of decades and those that vary seasonally or year to year.

In some areas of the United States, precipitation and temperature appear particularly well correlated with signals from the seasonal El Niño-Southern Oscillation (ENSO) cycle, as represented by sea surface temperatures or atmospheric indicators such as the Southern

Oscillation Index (an index of the surface pressure gradient across the tropical Pacific between Tahiti and Australia) and the Central North Pacific index. In turn, this association supports an apparent relationship between the ENSO indices, snowmelt, and streamflows. Cayan, Redmond, and Riddle (1999) have demonstrated, for instance, a clear correlation between atmospheric pressure differences tied to ENSO events and streamflows in the western United States. This association looks more robust than the association between ENSO and precipitation, even though the physical connection between ENSO and precipitation is more direct. Clark, Serreze, and McCabe (Clark, Serreze, and McCabe 2001) show that, in the Columbia River basin, ENSO events correlate closely with snowpack conditions and the magnitude and timing of snowmelt.

Given evidence of these connections, the apparent association between ENSO signals and streamflows have been used to anticipate disturbances in hydrologic regimes. From the research community, Dettinger, Cayan, and Redmond (1999) recently applied knowledge of the association in a long-lead forecast for the 1999-2000 flow season issued at the start of that season. Their forecast suggested a heightened probability of higher-than-normal streamflows in the northwestern part of the United States due to La Niña conditions. Pulwarty and Melis (2001) describe how reservoir managers in the Colorado River system effectively used ENSO information in the 1997-1998 flow season to anticipate higher-than-normal flows.

In the popular media, one of the best-known examples of the utilization of ENSO signals comes from California. Forecasts of a strong ENSO anomaly prior to the 1997-1998 flood season—in this case, an El Niño signal—led state and county officials to organize a community preparedness summit in October 1997 to identify measures local governments could take to mitigate the potential impacts of the El Niño anomaly. After the summit, Los Angeles County, Oakland, and other cities cleared hillside spillways of debris to minimize erosion and flooding, distributed sand and sandbags to high impact areas, and created special task forces and centralized emergency response centers to assess conditions of levies and berms and to monitor high risk areas. Climate forecasters as well as federal and state emergency planners are on record saying that, without the early warning, damages to property and loss of life likely would have been worse (Federal Emergency Management Agency 1998).

More recently, Tillamook County, OR, used a seasonal ENSO forecast to better prepare itself for the 1999-2000 flood season. Bolstered by a long-range seasonal forecast from the U.S. National Weather Service that anticipated an “elevated risk” of heavy precipitation in Tillamook due to wintertime La Niña conditions (Keeton 1999), local county emergency management staff, elected county officials, Oregon’s governor, and the Oregon congressional delegation joined the U.S. Army Corps of Engineers to fund and construct several emergency measures to mitigate the effects of possible flooding. Tillamook officials credit these measures—which were put in place two days before a major flood hit the Tillamook area in November 1999—with reducing flood damages substantially.[1] A similar dynamic played out in Snohomish County, WA that same water year,[2] where the anticipation of La Niña conditions helped justify advanced measures by the U.S. Army Corps of Engineers to protect a wastewater treatment plant that was at risk of flooding.

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[1] The director of the Tillamook County Department of Emergency Management noted that the measures implemented in anticipation of La Nina conditions cut losses in the November 1999 flood to roughly $3 million in damage. A flood of similar magnitude in 1996 had caused $53 million in damage in the same area (Manning 2000).

[2] Water years run from October 1 through September 30 of the following year. For example, all dates from October 1, 1999 to September 30, 2000 are categorized as occurring in water year 2000.

3. La Niña in the Pacific Northwest

The Northwest examples mentioned above benefited from a large body of research in the region spanning more than a decade by numerous investigators (Cayan and Peterson 1989; Cayan and Redmond 1994; Cayan and Webb 1992; Greenland 1994; Kahya and Dracup 1993; National Water and Climate Center/Natural Resources Conservation Service 1997; Redmond and Koch 1991). This work suggests that, in the Pacific Northwest, El Niño events contribute to warmer winter temperatures and reduced precipitation, snowpack, and streamflows on the one hand and La Niña events contribute to higher-than-normal wintertime precipitation and streamflow on the other.

The La Niña correlations, in particular, have appeared evident throughout the Columbia River Basin in sub-basins that vary in scale and hydrologic characteristics. Flows in watersheds in the interior of the basin, in catchments that lie entirely west of the Cascade Mountains and drain to the Columbia River, and in coastal basins draining directly to the Pacific Ocean all appear to be affected by the occurrence of a La Niña. Using the preceding summer Southern Oscillation Index (SOI)—with negative summer SOI values indicating warmer El Niño episodes and positive SOI values indicating cooler La Niña events—we can produce evidence of these relationships both with respect to the size of mean flows and the number of times that important mean flow thresholds are exceeded.

Mean Daily Flows and ENSO Events

Using simple correlation measures, daily mean discharges in the high flow season and summer SOI values appear strongly related in a number of different-sized catchments in the

Pacific Northwest.[3] For example, consider the Dalles dam in Oregon (see Figure 1), past which moves runoff from nearly all of the 625,000 square kilometers of the interior portion of the Columbia River basin (that is, the portion of the Columbia basin that lies east of the Cascade mountains). A nonparametric Spearman rank correlation test between the median of the daily mean flows and the summer SOI is significant at the 0.01 level (meaning one can reject the null hypothesis that flows and the summer SOI are independent at the 0.01 level). This is the case, even though high flows are fed primarily by snowmelt and the hydrosystem has significant storage and shaping capabilities above the gauging site. West of the Cascade Mountains in the 12,500 square kilometer portion of the Willamette watershed above Albany, OR, the corresponding Spearman correlation coefficient again is significant at the 0.01 level. This basin also has some storage and shaping capability, but high flows are less dependent on seasonal snowmelt runoff. Finally, along the Oregon coast in the 1,700 square kilometer Nehalem River watershed, the Spearman correlation coefficient also is significant at the 0.01 level. This latter catchment has no appreciable storage and is not driven primarily by snowmelt.

We also see the association between flows and summer SOI values by examining a time series that isolates the distribution of flows for given days in the year. Adopting the approach described in Dettinger, Cayan, and Redmond (1999), we can compare the number of times that

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[3] The results reported in this section cover flows from 1934 to 1999 (for the Columbia and Willamette rivers) and 1940 to 1999 (for the Nehalem river). Flow records come from the National Water Data Storage and Retrieval System at http://waterdata.usgs.gov/nwis-w/US/, last accessed December 22, 2000. Although daily mean discharge data are available for a longer historical period in each of the basins discussed, the most complete SOI data series are from the mid-1930s onwards. These latter data come from ftp://ftp.ncep.noaa.gov:/pub/cpc/wd52dg/data/indices/ (last accessed on 10/9/01) and have been recalculated to accommodate different reporting formats. Note that we are referring in this section to daily mean flows rather than instantaneous peak flows. We examine the latter in section 5.

high flows for a particular day in the year occur in years that are dominated by a La Niña to the number that we would expect by chance alone. For instance, there are 60 values for daily mean flows on January 1st in the historical record for the Nehalem River (from 1940 through 1999). We place each of the 60 flows in the relevant third of the historical flows—the lowest 20 flows in the bottom third, the next 20 flows in the middle third, and the highest 20 flows in the top third. If flows are independent of the occurrence of a La Niña, we would expect, on average, that one third of the flows during La Niña years would be in the bottom third, one third in the middle third, and one third in the top third. We find, however, of the 13 years from 1940 to 1999 that were characterized as La Niña years, none had January 1 flows that were in the bottom third, three had flows in the middle third, and 10 (more than 75%) had flows in the top third. During the roughly 2,370 dates in the high flow season in Nehalem's historical record that occurred in La Niña years (13 years x 182 days/high flow season, 1,061 dates (roughly 45%) had flows lying in the top third of the flow distribution. If flows were independent of the occurrence of a La Niña, one would expect that only 790 dates (33%) would lie in the top tier.

Tables 1A, 1B, and 1C show the proportion of instances in which a flow lies in the bottom, middle, and top third of the distribution of flows over the historical period in the Columbia, Willamette, and Nehalem catchments, for both La Niña and non-La Niña years.[4] The bottom row in each of the tables shows the number of dates in the relevant time period in each of

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[4] For our purposes, we have defined November 1 to April 30 as the high flow season in the Nehalem and Willamette (as well as in all the other basins discussed in the text except the Columbia River watershed as gauged at The Dalles), a period that accounts for roughly 90% of the high flows during the record in each basin. The separation of the records into three tiers reflect flows only over this period. In the Columbia, we defined the high flow season as April through July. This period includes more than 75% of the highest flows in the historical record.

the two types of years, while the right-most column shows the number of dates in each third.[5] The numbers in the center of the table represent the proportion of dates in that column that lie in each third. Thus, the three proportions in each column add up to 1.0. In each of the basins, a higher proportion of flows (45%) lie in the top third of flows in La Niña years than mere chance would suggest. A χ^2 test of the independence of the distribution of flows split into thirds and the occurrence of a La Niña leads us to reject a null hypotheses of independence at the 0.01 level in each of the three basins.

Counts of High Mean Flow Events

Clearly, both the χ^2 tests and the simpler Spearman tests only suggest that a relationship exists between the occurrence of a La Niña and high flows. This association between high daily mean flows and a La Niña occurrence does not permit one to assess whether the most critical high flows might be more frequent or of a higher magnitude; that is, neither test says anything definitive about the likelihood of flood events. One way to get at this latter issue is through a partial-duration time series analysis of the flows in each basin. Such an approach models all flows in a historical record above a given threshold discharge and tests—based on an assumed

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[5] In principle, for each basin represented in Table 1, each of the row totals should represent exactly one third of the observations in the flow record. However, due to missing data and rounding and because of differences in seasonal definitions and the available flow record for each basin, the row totals are not identical within individual basins or across basins.

distribution of these events—whether there exists a significant relationship between the number of flows exceeding the threshold and a set of independent variables of interest.[6]

The dependent variable in our partial duration analysis is the count of historical daily mean flows during the high flow season that equal or exceed three quarters of the maximum seasonal flows in the historical record; that is, for each basin we determine each year's maximum mean daily flow and select the 75th percentile of this flow distribution as the "high flow" threshold. We define all flows equal to or exceeding this threshold as high flows. By this definition, most years will not have any high flow events (count equals zero), while some years may have multiple events.[7] The independent, right-hand-side variable is either the average SOI for the preceding June through November or a binary variable indicating whether a La Niña event is occurring. In both cases, we assume a Poisson process.

Based on the SOI measure, the ENSO signal is a significant predictor of high flow events in the Nehalem and Willamette basins at roughly the 0.05 level of significance. The La Niña binary variable is significant in the Nehalem at the 0.01 level, but not in the Willamette. Goodness-of-fit χ^2 tests in each basin for each of the two indicator variables suggest that the Poisson process fairly represents the count of high flow events, and tests of significance with an

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[6] In the extensive literature on partial duration analysis of hydrologic time series, in addition to the Poisson process that we assume, common distributions for approximating the frequency of high flow events include the generalized Pareto, negative binomial, log-normal, and log Pearson type III distributions (Duckstein, Bárdossy, and Bogárdi 1993; Keim and Cruise 1998; Meirovich et al. 1998; Rasmussen and Rosbjerg 1989; Rasmussen and Rosbjerg 1991; Rosbjerg, Madsen, and Rasmussen 1992; Shane and Lynn 1964; Todorovic and Zelenhasic 1970).

[7] Our approach includes an adjustment for serially correlated high flows to maintain the assumption of independent events necessary for the Poisson model. In particular, we counted flows as high flow events only if the events occurred at least seven days apart. We also used three days as the threshold for independence, with no appreciable difference in the results.

alternative negative binomial specification against overdispersion in the Poisson process for both catchments confirmed the validity of the Poisson assumption.[8]

In the Columbia basin, the ENSO signals at first glance also appear significant at similar test levels for both the SOI and La Niña specifications. However, this is only if we run roughshod over the data. A goodness-of-fit χ^2 test in the Columbia basin indicates that we should reject at the 0.10 level our assumption of a Poisson process for depicting high flow counts in the case of both the SOI and La Niña data. When we turn to a negative binomial specification, we can reject the notion that the dispersion parameter equals zero—the value of the parameter in a true Poisson process—at the 0.01 level. This alternative specification, however, yields only a moderately significant SOI variable at the 0.10 level (and not even at this level for the La Niña specification). The greater capability to shape flows in the Columbia basin and the abundance of hydrologically diverse subwatersheds within the large basin appear to mute the simple ENSO signal.[9]

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[8] Overdispersion refers to a process in which the variation in the count data is more than would be found in a true Poisson process. Omitted variables are one common source of such overdispersion.

[9] An alternative analysis of the hydrologic data similar to our above divison of the flow records into thirds could estimate a model based on the summation of day-specific high flow events over the entire course of each water year. Following Cayan, Redmond, and Riddle (1999), the upper tail of historical flows (such as the top 5%) can be isolated for each day in the water record. Summing all of the flows that exceed their respective thresholds in a given water year would provide a left-hand-side count variable that could be regressed against the SOI variable or a binary La Nina variable. When carried out, such an estimation appears to yield a significant relationship (0.01 level) in each of the three basins. However, this significance is misleading because the approach does not control for the serial correlation of flow events, thereby violating a fundamental assumption of the Poisson process. In fact, goodness-of-fit χ^2 tests suggest that we can reject the assumption of a Poisson process at the 0.01 level in this alternative approach.

4. Using ENSO Signals Proactively

Notwithstanding the underperformance of the ENSO prediction model in the expansive Columbia Basin, the partial duration analysis appears useful for understanding the connection between ENSO and high flow events in the two smaller catchments. The Nehalem watershed offers a particularly interesting application of the ENSO prediction model, in that it exemplifies coastal basins that, in Oregon at least, typically have minimal or no capability to store water during high seasonal runoff. Absent such storage and ability to shape river discharges to avoid high peak flows, many coastal basins are prone to damaging floods. This exposure to peak flows, particularly in basins susceptible to flash flooding, places a premium on response capabilities. For natural hazards planners and emergency managers, a long term seasonal climate forecast may enable them to reduce the impact of the high flows by positioning resources such as sand bags and equipment, obtaining additional local financial resources for emergency management activities, and pre-planning to define specific responsibilities and update logistics..

The partial duration ENSO model may help to improve such seasonal anticipation. The Poisson process—even absent ENSO indicators—matches the observed frequency of flood events quite well, but it improves with the addition of a binary La Niña or summer SOI indicator. For example, if, as before, we define a high flow as any independent daily mean flow that exceeds the 75th percentile of the annual maximum daily mean flow, the Nehalem record shows that 75% of the water years in the record have 0 high flow events, 20% have one event, and 5% percent have two events. The Poisson model without ENSO indicators estimates probabilities of 74%, 22%, and 3% for zero events, one event, and two events, respectively. Thus, it barely underpredicts zero- and two-event water years and overpredicts one-event water years. The addition to the regression model of a zero/one indicator to indicate the no-occurrence or occurrence of a La Nina year slightly improves the fit to 76%, 20%, and 4%. The SOI indicator performs similarly.

The marginal improvement in depicting the observed record that we see when we include ENSO indicators appears modest, but it nonetheless facilitates the estimation of the expected change in the number of high water events for a given change in the ENSO signal. Using the binary La Niña indicator, for example, the regression model estimates that, in non- La Niña years, the probability of having one or more flood events is only about 0.17. In contrast, in years when a La Niña does occur, the probability of having one or more flood events is 0.5. With this increased likelihood of high flows, emergency managers and planners may find it politically feasible to plan more aggressively for flooding.

Figure 2 shows how the estimated probabilities change as a function of the continuous SOI variable. The x-axis depicts the summer SOI as it moves from its minimum to its maximum (over the 1940-1999 period of the Nehalem time series), while the y-axis shows the estimated probabilities of event counts. The lines themselves represent the estimated distributions for zero events in a water year, one event in a water year, and two events in a water year, as a function of the summer SOI. As the summer SOI value increases from left to right on the graph, El Niño conditions attenuate, giving rise to La Niña conditions. The probability of having zero flood events decreases from 0.93 when the SOI is at its minimum value, to 0.75 when the SOI equals 0.0, to 0.43 when the SOI is at its maximum value in the time series. Conversely, the probability of one-event water years increases more than five-fold over this range. The probability of a two-event season is still low during a La Niña event, but it steadily increases to a high of 0.15 at the SOI extreme. A 0.5 probability that a water year will have at least one high flow event (the abscissa of the point at which the zero-event line intersect the 0.5 probability ordinate) occurs when the summer SOI value reaches 1.5.

5. Ambiguity in ENSO Signals

Although the above Nehalem example suggests a potential role for ENSO signals in flood planning, its relevance will depend in part on the physical characteristics of individual watersheds and on the particular flow metrics of interest to floodplain managers. An apparently strong ENSO signal in a particular region may be of little use for some individual catchments in the region, either because these catchments have unique hydrologic characteristics or because flow measures other than mean daily discharge (for example, flood stage) are critical for initiating responses and coordinating mitigation efforts. We can see this by examining in more detail a number of Oregon coastal basins and different high flow definitions.

Variation in the Strength of ENSO Signals Across Different Watersheds

The intensity and duration of precipitation and air temperatures typically are the key ingredients in increasing river discharges in most basins, but other factors can play major roles in whether a high flow results in a flood event. Along Oregon's coast, for example, floods in some smaller rivers that empty into bays often are caused by storm surges and high tides in concert with heavy precipitation. These surges and tides pile up bay water and decrease the rate at which streamflows can be discharged to the open sea. More generally, the particulars of a watershed—its elevation, susceptibility to blockage, channel geometry, gradient, and vegetative and soil characteristics—also can fundamentally shape runoff independent of the climatic conditions that it shares with other watersheds in a particular region.

The bottom part of Figure 1 displays three basins that lie within 70 miles of the Nehalem—the Wilson, Trask, and Siletz watersheds. Table 2 displays the same three sets of statistical measures that we presented earlier to characterize the ENSO-streamflow association, for the Nehalem and the three other coastal basins. Based on the simple Spearman measures (r_s) that appear in the second row, the association still appears statistically significant at the 0.01 level for two of the three additional basins, the exception being the Trask River, where the small sample size yields significance only at the 0.15 level. The proportion of daily mean flows in La Niña years over the time series that lie in the top third of flows is 0.4 or greater in each watershed (row 3), and a χ^2 test of the independence of the distribution of flows and the occurrence of a La Niña episode allows us to reject a null hypotheses of independence at the 0.01 level in all of the additional basins. Based on this evidence, the association between ENSO events and streamflows appears largely intact in each of the additional basins. When we use the partial duration model to look at more extreme flows, however, the relationships become more nuanced. The SOI variable is significant in both the Wilson and Trask in row four of Table 2—at the 0.1 level or better—but the La Niña variable is not significant at this level in these two basins. Neither variable is significant at the 0.1 level in the Siletz (which has 60-plus years of data).

Variation in the Strength of ENSO Signals Across Different Flow Thresholds

In addition to differences in ENSO signal strength that arise among different watersheds, the association between ENSO and flow indicators varies with respect to the different measures of high flow. As we change the threshold for high flow, the apparent strength of the ENSO-flow relationship changes. The definition of thresholds is thus an important feature of an analysis using a partial duration approach (Martins and Stedinger 2001).

For example, consider the numerical results displayed in Table 3. These summarize the significance of partial duration analyses for the Nehalem, Siletz, Wilson, and Trask basins when we use the SOI indicator and vary the definition of the flow threshold of interest. Column B in Table 3 for the Nehalem repeats the results shown in the fourth row for the Nehalem column in Table 2, where we established the high flow threshold as the 75th percentile in the distribution of annual maximum flows over the historical time series (remember that, under this definition, many of the years in the record will have zero flows that equal or exceed the threshold). As the results in column B of Table 3 show, the count of high flows appears to be correlated with the SOI indicator at the 0.1 level for three of the four basins, the exception being the Siletz watershed as noted above.

If we greatly relax the threshold and define a high flow as any flow that falls in the 95th percentile of all daily flows in the flow season for each watershed, most years in each of the four basins have more than one high flow event, with some years having five or more high flow events. The SOI indicator continues to be significant at the 0.1 level in three of the four basins, as indicated in column C of Table 3. The Siletz continues to be an exception. If we relax the threshold even more by setting it at the 90th percentile of all daily flows in the high flow season, even more events are counted as high flow events, but the significance of the SOI indicator as an explanatory variable decreases in three of the four basins (column D) as compared to the 95th percentile threshold. The SOI indicator seems more significantly related to high flow events as the definition of “high flow loosens, but only up to a point. Results of going the opposite direction and setting the threshold at a higher level confirm this ambiguity. Column E of Table 3 shows that a tighter threshold than our original specification of the 75th percentile of maximum annual mean flow (the 85th percentile) results in the SOI indicator continuing to remain significant at the 0.1 level in two of the basins, losing its significance at the 0.1 level in one of the basins, and becoming newly significant at the 0.1 level in the remaining basin.

The non-uniform change in the apparent strength of relationship between ENSO conditions and the number of flood events as the flood threshold varies complicates the characterization of the ENSO and flow connection. For example, the U.S. Geological Survey defines the discharge level and stage height that constitute a flood at many of its gauging stations. In three of the coastal basins listed in Table 3 (Nehalem, Siletz, and Wilson), the thresholds discussed above are high relative to the discharge levels that constitute flood flows by the U.S. Geological Survey definition. The latter, lower thresholds yield a median of two flood events per water year in both the Nehalem and Siletz, and a median of one flood event in the Wilson drainage per water year. The same lower thresholds yield as many as four flood events in both the Siletz and Wilson drainages, while the Nehalem has had as many as six flood events by this latter definition. A partial duration analysis in each basin using the U.S. Geological Survey discharge levels yields insignificant p-values; that is, we cannot reject the null hypothesis that there is no relationship between the number of flood events and the ENSO indicator.

Mean Flows and Instantaneous Flows

The absolute value of the flow that one sets as the threshold of interest clearly shapes whether one is able to find a significant relationship between ENSO indications and flood events, but whether one uses instantaneous peak flows or daily mean flows to define this measure also can be important for effective flood management. Very high peak flows may be troubling even if of short duration, because they inundate areas that are normally left dry in flood events. On the other hand, lower peak flows of longer duration, while inundating a smaller area, may be difficult because they force a business to close for several days. Choosing which of these standards to characterize a flood—and which one to examine prospectively in an analysis—can be problematic. Fortunately, the relationship between instantaneous peak flows and mean flows is generally strong.

At the national level, Vogel, Zafirakou-Koulouris, and Matalas (2001)—citing more than 100 years of records in the Hydro-Climatic Data Network (HCDN) Streamflow Data time series and personal communications from the U.S. Geological Survey—note that mean daily flow is, on average, 80% of the instantaneous maximum flow, with the standard deviation of this ratio only 0.2. In the Oregon coastal basins discussed earlier, this close fit between mean and instantaneous flows is generally born out. Using a 15-year time series of instantaneous flows[10] in three of the basins, we can see in row 1 of Table 4 that the ratio of average daily flow to instantaneous maximum daily flow exceeds 0.9 in all basins. The standard deviations of these ratios that appear in row 2 of the table lie between 0.08 and 0.1.

The relationship between flows in the upper tails of daily mean and instantaneous flows appears somewhat weaker. Rows 3 to 6 of Table 4 show the percentage of dates in which high-mean daily flows and high instantaneous flows—each defined at several points on their

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[10] The instantaneous flows used to calculate the summary numbers in Table 4 are not true peak flows, but rather are defined on a 30-minute basis. That is, they represent flows measured at 30-minute intervals, 48 time periods per day that run from midnight to midnight. For the Siletz and Wilson basins, the flow records cover the period between October 1, 1986 and July 31, 2001, except for days in the 1988 water year (those data are missing). The Nehalem record is also missing data for the 1993 water year, as well as for the 1988 water year. All of these data were provided courtesy of Jo Miller of the U.S. Geological Survey office in Portland, OR, and should be viewed as provisional.

respective distributions—occur on the same date in the time period. If we look at the mean and instantaneous flows in the top 10% of their respective distributions (row 3), the dates overlap at least 93% of the time. A definition of high flows as those in the top 5% of the respective flow series (row 4) yields comparisons somewhat lower, but there is still at least a 90% overlap in each basin. As we look toward the tails of the distributions at the top 1% of flows (row 5), the overlap drops still further, as low as 80% in the case of the Siletz. And finally, if we examine annual maximum daily mean streamflows and annual maximum instantaneous streamflows (row 6), the maxima occur on the same date less than one-third of the time. This latter result may reflect in part the arbitrariness of parsing flows into 24-hour increments that run from midnight to midnight—a potentially misleading characterization when high instantaneous flows occur close to midnight—but it also evidences the unique conditions that often give rise to very extreme events.

Even though the relationship between mean flows and instantaneous flows appears strong in some cases, the decreasing overlap between measures of mean flow and those of instantaneous flows as one moves to the upper tails of the two flow distributions complicates the characterization of the ENSO-flow relationship. Long time series of instantaneous flows that can be used to parameterize regression and prediction models are generally unavailable for most watersheds, so proxy measures such as mean flows are used. If short-lived but high-peaked instantaneous flows are of interest to flood managers and planners, proxy measures that correspond poorly to the part of the instantaneous flow distributions that are of interest will make it difficult to use ENSO signals proactively in seasonal flood management and planning.

On the other hand, the value of seasonal ENSO signals may be high if high daily mean flow—which represents a longer-duration period of high flow than the instantaneous measure—

is the more critical metric. In the February 1996 winter floods in western Oregon and Washington, for example, the Nehalem and other gauging records show that daily mean flows that exceeded the 75th percentile mean occurred on three to four consecutive days. With only a few exceptions, peak flows and river stages during this period were well below all-time records yet the persistence of the high mean flows was devastating, forcing more than 30,000 residents of the two states from their homes, leading to the designation of 18 Oregon and 13 Washington counties as disaster areas, and causing hundreds of millions of dollars of uninsured property losses.

6. Conclusions

The association between ENSO events and precipitation and streamflow has attracted abundant attention from the research community, arguably in large part because the relationship appears strong and helps to justify continued investment in climate and hydrologic research. As noted above, across a number of watersheds of differing scales and hydrologic characteristics, higher precipitation and streamflows appear closely linked to La Niña events using a variety of correlative measures. This has spawned efforts to isolate region-specific teleconnections to ENSO signals, and to forecast regional-level precipitation and streamflow anomalies based on these signals. Thus, for example, we might forecast higher-than-normal streamflows in the Pacific Northwest during La Niña years, and lower-than-normal streamflows that year in the upper Mississippi and Ohio River basins (Dettinger, Cayan, and Redmond 1999). This capability has led to interest among policymakers and managers in using ENSO forecasts to improve flood planning, and several apparently successful applications of ENSO forecasts have recently emerged in the Pacific Northwest, California, and the Southwest.

Given the apparent clarity of ENSO signals, both the research and policy communities have shown eagerness to further utilize ENSO forecasts for flood planning. However, there are numerous obstacles to greater acceptance of ENSO forecasts for flood planning, four of which we identify here.

First, the relationships are neither straightforward nor simple. As described above, the apparent association of ENSO signals and streamflows shows up only in some basins and some years and thus cannot be relied on with certainty. The winter of 2000-2001, for example, exhibited a neutral ENSO signal, but strong El Niño-like conditions persisted in the region and produced one of the driest winters on record. Moreover, there is a wide range of atmospheric and oceanic factors that may complement or attenuate ENSO events. During certain phases of the Pacific Decadal Oscillation, for example, ENSO signals appear to be strongly correlated with streamflows in many parts of the Northwest while, in other phases, the same ENSO signal shows little correlation with streamflow (Koch and Fisher 2000). Vaccaro (2000) has developed a regression model that includes this signal—along with almost 20 other atmospheric, oceanic, and hydrometeorological indicators—to provide long-range forecasts of fall inflows to a reservoir system on the west side of the Cascades east of Tacoma, WA. These other indicators add significantly to the predictive power of the model, implying that a forecast based only on ENSO signals may be overly simplified or, in some cases, misleading. There are considerable opportunities for expanding the range of indicators examined in longer-term forecasts beyond simple ENSO conditions.

Second and related, site-specific features critically shape the response of a watershed to an ENSO event. Adjacent watersheds exposed to the same ENSO-related weather event may experience dramatically different effects from the event.[11] The differences depend on both the physical characteristics of the respective basins—their gradient, land cover characteristics, and influence of tidal action, for instance—and the spottiness of the event. Intense precipitation may "park" over one part of a basin for several days and not over other parts. Different settlements within a basin may be particularly poorly situated, either with respect to natural features (such as at the confluence of two rivers both affected by relatively moderate ENSO events) or because of past land use and infrastructure choices. Site-specific information on precipitation and river flows is needed to better understand the likely effects of ENSO events, yet the density of weather and river gauges is notoriously sparse. This shortcoming is problematic both for researchers attempting to examine the long-term relationship between precipitation, flow, and climate signals, and for seasonal flood planning. Even more critically, but outside the scope of this paper, a denser network of rain and flow gauges to inform short-term flood operation is sorely needed, since emergency managers must mobilize resources and make evacuation decisions in the short time span of flood fighting where information is at a premium.

Third, the characterization of high flows is of crucial importance. Even if one can establish a statistically significant relationship between ENSO signals and river flows, the flow metric and statistical test need to be both suitable for prediction and relevant to the needs of a flood planner

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[11] In the February 1996 floods along the Oregon coast, for instance, both coastal and interior precipitation recording stations recorded more than 20 inches of rain in a five day period. The precipitation produced flows with a recurrence interval of more than 140 years on both the Nehalem and Wilson drainages, while the recurrence interval was only eight years in the Nestucca drainage (Tillamook County 1996; U.S. Army Corps of Engineers Undated).

or manager. Evidence of a simple correlation of ENSO signals and higher mean flows does not allow one to assess the marginal probabilities that certain high flow events will occur. This latter can be done in an analysis of count outcomes, with an assumed distribution of the number of times that a high flow event occurs tested against the actual record of occurrences of the event. Different event metrics (such as instantaneous peak discharge, highest two-day mean flow, flood stage) can lead to different conclusions about whether ENSO signals are relevant for flood planning. The definition of the event of interest can determine whether it is even possible to discern a relationship between ENSO signals and flooding. Using ENSO signals prospectively might be seen as a more credible exercise by end users if we knew which flow metrics appear the most relevant for local flood stakeholders and if we had a better understanding and record of flood damages at a local scale (Pielke and Downton 2000). To this end, we are currently conducting research in the Pacific Northwest.

Finally, we need a better understanding of the ways in which flood planning and management can take advantage of seasonal flood forecasts. A perfect forecast may be useless if there are no opportunities to use the forecast to change flood management. As Jones, Fischoff, and Lach stress (1999), for such information to be transferred and incorporated into policies and operational decisions, the information needs to be relevant to the specific decision or policy under consideration, and match the spatial and temporal scale at which decisions are being made. It also needs to be compatible with current decision procedures and accessible to the decisionmakers who, in turn, need to be receptive to it. In short, producers of scientific information must ensure that such information accommodates the characteristics of the decision making process itself rather than expect that the process will eagerly embrace new input.

Unfortunately, the connections between the physical science of climate forecasting and the use of ENSO forecasts in flood mitigation are still somewhat unformed. Climate modelers have to understand the needs of flood planners as much as flood planners need to have confidence in the science of ENSO forecasts. Opportunities exist to help strengthen the connection between researchers and practitioners and to disseminate the findings of climate research, but clearly different reward structures prevail for each group. The culture of science rewards journal publications and a tightly bound research agenda which, some commentators have observed, act as constraints to the transfer of knowledge to practitioners (Mileti 1999). And although it has increasingly become axiomatic that research needs to justify itself, efforts to provide such justification typically emphasize a relatively static "education" of the user. Embracing stakeholders in agenda setting and research design, and joining social, behavioral, and physical researchers in truly collaborative problem solving is a popular goal at the rhetorical level, but one that continues to be frequently ignored in practice.

Using seasonal climate forecasts to improve flood planning and management is without doubt a challenge. Not only will it require disciplinary integration between the natural and social sciences, and greater interaction between researchers and practitioners, but such an effort will be set in a political framework where too often local, state, and federal flood policies pull in different directions. Efforts to integrate ENSO forecasts in flood planning will require a better understanding of these institutional links.

Table 1. Distribution of Mean Daily Flows, by ENSO Condition

(a) Nehalem River Flows (1940-1999)*

flow distribution	**Non-La Niña Year**	**La Niña year**	**Total**
bottom third	0.37	0.22	**3644**
middle third	0.33	0.34	**3606**
top third	0.30	0.45	**3625**
Total	**8518**	**2357**	**10875**

*November through April flows

(b) Willamette River Flows (1934-1999)*

flow distribution	**Non-La Niña year**	**La Niña year**	**Total**
bottom third	0.38	0.18	**4003**
middle third	0.32	0.37	**3972**
top third	0.30	0.45	**3987**
Total	**9424**	**2538**	**11962**

*November through April flows

(c) Columbia River Flows (1934-1999)*

flow distribution	**Non-La Niña year**	**La Niña year**	**Total**
bottom third	0.38	0.17	**2709**
middle third	0.32	0.38	**2677**
top third	0.30	0.45	**2666**
Total	**6344**	**1708**	**8052**

*April through July flows

Table 2. Summary Statistics of Flow and ENSO Relationship, Coastal River Basins

	Nehalem	Siletz	Wilson	Trask
1. area (miles^2)	667	202	161	145
2. r_s significance (flow and SOI)	< 0.01	< 0.01	< 0.01	< 0.15
3. La Niña proportion in top third	0.45	0.43	0.43	0.40
4. model significance (count and SOI)	0.03	0.18	0.10	0.05
5. model significance (count and La Niña)	< 0.01	0.43	0.16	0.16

Table 3. Partial Duration Analyses of Daily Mean Flows, Coastal River Basins

A. Basin Name	**B.** threshold = top 25% of max flows	**C.** threshold = top 5% of all flows	**D.** threshold = top 10% of all flows	**E.** threshold = top 15% of max flows
Nehalem	0.03	< 0.01	0.63	0.05
Siletz	0.18	0.20	0.12	0.08
Wilson	0.10	0.06	0.69	0.18
Trask	0.05	0.05	0.15	0.09

Table 4. Comparison of Mean Flows and Instantaneous Flows

	Nehalem	**Siletz**	**Wilson**
1. ratio of mean daily/max instantaneous	0.94	0.92	0.92
2. standard deviation (of ratio of mean/instantaneous)	0.08	0.10	0.10
3. max mean daily & max instantaneous, % congruence	31	29	29
4. top 1% daily & max instantaneous, % congruence	89	80	82
5. top 5% daily & max instantaneous, % congruence	90	91	91
6. top 10% daily & max instantaneous, % congruence	95	94	93

Figure 1
Columbia, Willamette, and Oregon Coastal Basins

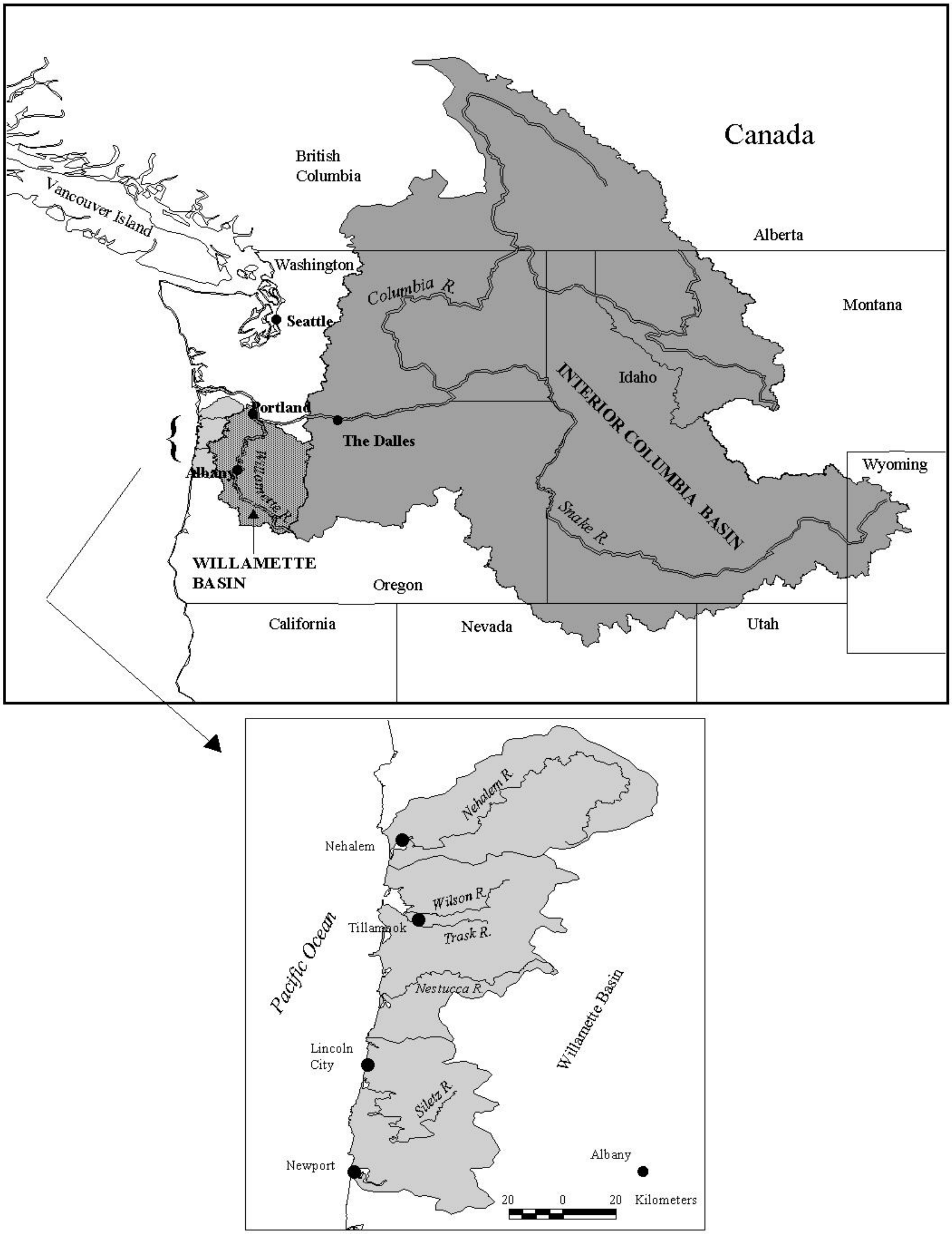
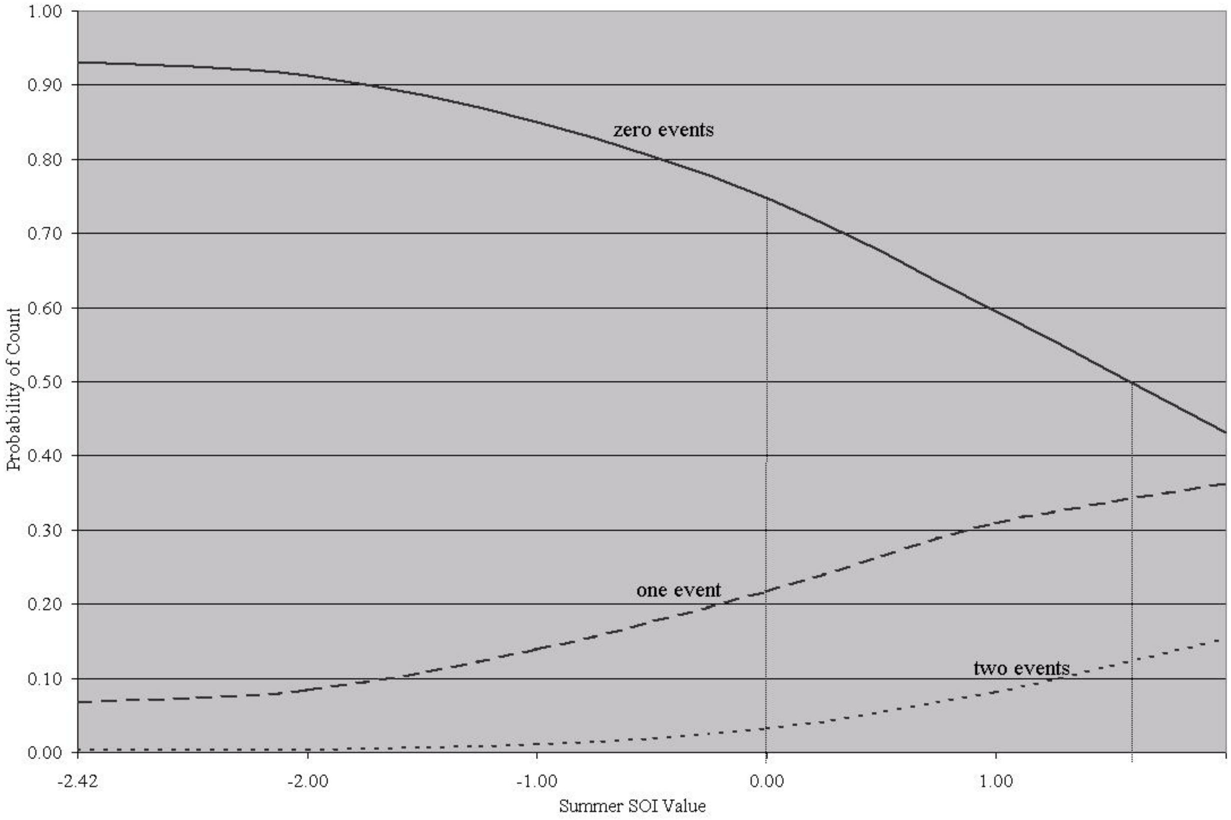


Figure 2
Probability of Flood Events per Water Year as Function of Summer SOI
(Nehalem River, 1940-1999)



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