Integration of Climate Information and Forecasts into Western US Water Supply Forecasts

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Abstract

Since the early 1900's, the Natural Resources Conservation Service and cooperating agencies have produced long-lead seasonal volumetric water supply forecasts throughout the western US. These statistical regression-based forecasts primarily rely on measurements of current snowpack and proxies of soil moisture such as antecedent streamflow and autumn precipitation. It has long been recognized that the largest source of forecast uncertainty and error is the amount of precipitation falling between the forecast issue date (e.g., January 1st) and the end of the target season (e.g., September). Seasonal climate information and forecasts offer the potential to improve the skill and lead time of water supply forecasts by reducing uncertainty about future precipitation. This chapter reviews the use of climate information in operational water supply forecasts at the Natural Resources Conservation Service's National Water and Climate Center. The use of climate information in other operational hydrologic forecasting agencies, such as the National Weather Service and the Salt River Project, are also highlighted. While there are benefits gained from using climate information in water supply outlooks, there are also potential hazards arising from climate forecast use and abuse. In particular, there is an acute need to manage risk and expectations about forecast skill among forecasters and users alike.

Operational Water Supply Forecasting

Snowmelt provides approximately 80 percent of the streamflow in the West. Streamflow forecasting in the West, therefore, is strongly dependent on snow measurements. The Natural Resources Conservation Service (NRCS), in partnership with other federal and state agencies, conducts snow surveys in 12 western states and Alaska. The NRCS integrates hydrometeorological data from 1100 manual snow courses, 670 automated SNOTEL (SNOwpack TELemetry) sites, 575 stream gages, 310 major reservoirs, and 3200 climatological observing stations to create basin and watershed analyses and water supply forecasts.

These forecasts are produced monthly, January through June, in partnership with the National Weather Service (NWS) and local cooperating agencies, such as the Salt River Project in central Arizona. The forecasts discussed here are unrelated to water supply forecasts issued by NWS offices in the eastern US, such as the Mid-Atlantic River Forecast Center. The methodology and character of those outlooks are significantly different from western outlooks and, as such, the NRCS does not participate in their development or distribution.

During the 2002 forecast season, four hydrologists at the NRCS National Water and Climate Center (NWCC) issued 11411 seasonal water supply forecasts for 709 locations to support water resource management activities. The primary recipients of these forecasts are agricultural, municipal, industrial, hydropower, environmental, and recreational water users.

Forecasts are developed using the statistical principal components regression technique described by Garen (1992). These regression equations are used to compute the median value of the seasonal water volume forecast distribution. A probabilistic error bound is then added to the forecast. The regression equations are developed using a "jackknife" technique involving the calibration of an equation on all but one historical year of data and then using the equation to "hindcast" the single year that was removed. This process is repeated leaving out each historical year in turn until a full set of hindcasts is obtained. The width of the probabilistic forecast error bound is proportional to the root mean squared error between these jackknife hindcasts and their respective observations. This error bound typically narrows as the season progresses as there is less uncertainty in the forecast.

A typical water supply forecast, as published, includes the name of the forecast location (e.g., "Lake Powell Inflow"), the forecast target season (e.g., "April-July"), the long term historical average flow volume, and the forecasted flow volumes corresponding to each of 10%, 30%, 50%, 70%, and 90% exceedence probabilities. Despite being statistically imprecise terminology, the 50% exceedance probability, or median, value has traditionally been called the "most probable" forecast. Additionally, a forecast packet may include a map of the "most probable" forecasts, expressed as a percent of the long-term average. Although the forecasts are probabilistic, the forecasters' and users' focus is often on this "most probable" value.

Advanced forecasting tools and products are in development at the NRCS and other agencies. In the near future, long-lead information about peak flows, low flows, and number of days to a particular flow threshold will be routinely produced through the NWS Advanced Hydrologic Prediction System (AHPS). This Ensemble Streamflow Prediction (ESP) system involves the calibration of a hydrologic simulation model, model initialization using current watershed states, and forcing based on a number of observed historical meteorological traces. The output is a series of "possible future" daily hydrographs, from which the above mentioned characteristics can be derived. The NRCS NWCC is also actively developing this kind of capability, including an advanced spatially distributed hydrologic simulation model. Other agencies have also been using this kind of forecasting to operate complex reservoir and canal water distribution systems in the West (see for example Clark et al. [2003] which links a streamflow simulation model to the water distribution models of the Watershed and River System Management Program, WaRSMP).

History of Operational Climate Forecasts and Water Supply Forecasts

Taking advantage of seasonal climate forecast skill has been a long-standing moderate to high priority within water supply forecasting agencies. Church's (1935) seminal publication about snow surveying and water supply forecasting identifies precipitation variability during the runoff period (after forecast issuance date) as the largest source of forecast error. Schaake and Peck (1985) estimate that for the 1947-1984 forecasts for inflow to Lake Powell, almost 80% of the January 1st forecast error is due to unknown future precipitation; by April 1st, Shaake and Peck find that future precipitation still accounts for 50% of the forecast error.

There has also been a long history of attempting to incorporate seasonal climate forecasts into operational water supply forecasts. The NWS (then called the US Weather Bureau) started creating bi-monthly 30-day weather outlooks for internal use in 1943. In 1953, they began issuing these forecasts to the public. Shortly afterwards, the Columbia Basin Interagency Committee evaluated their usefulness in forecasting Columbia River streamflow (CBIAC, 1955). This report concluded that the potential benefit was great but that the actual skill was too low for practical use. Specifically, the report was concerned about the increased chance of incurring a major forecast "bust" when using the climate forecasts versus existing practices (i.e., assuming near-normal future precipitation). A later report (CBIAC, 1964) revisited the issue and found that forecast skill was improving, but it was still not satisfactory for operational considerations, particularly when applying the climate forecasts to geographically small basins (i.e., "downscaling").

The 1970s were an active period in climate and water supply forecasting. Although produced internally since 1958, the first seasonal (i.e., 90-day) temperature forecast was released to the public in 1974, with the first seasonal precipitation outlook following in 1978. As part of the long-range streamflow forecasting "Project Hydrospect", which began in 1971, William Arvola of the California Department of Water Resources (CDWR) reviewed all historical and ongoing research in seasonal climate forecasting (Arvola, 1975; Peters, 1984). In the fourth year of Project Hydrospect, CDWR began sponsoring research by the famed climatologist Jerome Namias, then at the Scripps Institution of Oceanography. The technical linkages between climate and streamflow forecasting in California grew in sophistication (Zettlemoyer, 1982). These activities also inspired Jim Marron, an operational NRCS water supply forecaster, to use the Southern Oscillation Index to forecast streamflows around Lake Tahoe and in Nevada beginning in 1976. Marron soon abandoned the practice because of the Southern Oscillation Index's lack of predictive skill in that region (J. Marron, personal communication, 2003).

Among the several other early attempts to use climate information in water supply forecasts, Schaake (1978), in northern Virginia, used the 30-day precipitation outlook in October 1977 to remove a series of "anti-analogues" from the available ESP input meteorological traces. Similarly, in the mid-1980s, Croley and Hartmann (1987) used climate outlooks subjectively to alter ESP traces in forecasting Great Lakes levels. This method has evolved into the objective procedures described by Croley (2000). In managing Lake Okeechobee, the South Florida Water Management District also employs this climate outlook-weighted ESP forecasting technique (Cadavid et al., 1999). The NWS currently has a variety of procedures for climate-weighting its ESP traces, ranging from a simple technique developed in 1995 by Larry Rundquist at their Alaska River Forecast Center to the complex method of Perica et al. (2000). The Colorado Basin River Forecast Center is currently testing no less than five different methodologies for climate-weighting its ESP traces (D. Brandon, personal communication, 2003). Most recently, in a non-operational environment, Hamlet and Lettenmaier (2000) are routinely producing real-time climate-weighted ESP traces from an advanced spatially distributed hydrologic simulation model. Similarly, the WaRSMP software package offers climate-based subsetting of its routine but non-operational ESP traces (D. Boyle, personal communication, 2003).

Just as the 1982-1983 El Niño was a focusing event for the climate community, so the 1983 Colorado River flood was equally focusing for the water supply forecasting community (Rhodes et al., 1984). Until April 1983, snowpack on the Colorado River basin was near average, and the median forecasted inflow to Lake Powell was similarly near average (109%). An exceptionally cold and wet spring ensued, followed by a rapid warming. The observed April-July flow, at over 210% of average, overwhelmed the already full reservoir system. Glen Canyon Dam sustained severe damage to its spillway tunnels because of the high volume of water it was passing. The integrity of the dam was threatened, and plywood board extensions were added to the top of the spillway gates to hold back the flow. As subsequent analysis revealed, this simultaneous occurrence of an exceptional El Niño and an exceptional flood remains imprinted in the in the institutional memory of water managers in the region.

Interest in climate and streamflow grew throughout the 1980s, spurred on by research characterizing El Niño's global and regional impacts, such as Ropelewski and Halpert (1986, 1987). Cayan and Peterson (1989) investigated El Niño and western US streamflow, which coincided with work being done by Redmond and Koch (1991) on the same topic. David Garen, one of Koch's students at the time, was also an operational water supply forecaster with the NRCS. Garen began using the Southern Oscillation Index (SOI) as a predictor variable in forecasting Columbia River Basin streamflow. Around the same time, in 1988, Tom Perkins, also an NRCS forecaster, began using SOI as a predictor in the Lower Colorado River and southern New Mexico (T. Perkins, personal communication, 2003). During this period, many other hydrologists, including counterparts in the NWS, were skeptical that factoring in El Niño information sufficiently increased water supply forecasting skill and did not adopt this practice until later. Robert Hartman, however, transferred to the NWS Colorado Basin River Forecast Center (CBRFC) in 1990 after being an NRCS forecaster during Perkins' and Garen's activities. At CBRFC, Hartman continued investigating the climate-streamflow connection and generally found discouraging calibration results in all areas except the Lower Colorado (R. Hartman, personal communication, 2003).

Although myriad research publications about El Niño and streamflow appeared (e.g., Cayan and Webb, 1992; Kahya and Dracup, 1993; Piechota et al., 1997; among many others), operational procedures generally remained unchanged for several years. The Salt River Project (SRP), a central Arizona water manager and a coordinator in the water supply forecasts, adopted the "Entropy Limited" precipitation model (Christensen and Eilbert, 1985) in 1988. Although this model is proprietary, it may be conceptually similar to the statistical multiple discriminant analysis model of Young and Gall (1992). This model uses air temperature and precipitation data at many global sites to produce probabilistic estimates of central Arizona precipitation and runoff. SRP developed a post-processor to convert the probabilistic forecast into a deterministic forecast (Reigle, 1998). SRP also conducts extensive statistical analysis of climate and winter streamflow (Skindlov et al., 2000), which are used to support water supply forecast activities. SRP hydrologists, like most operational water supply forecasters, consult the official Climate Prediction Center (CPC) seasonal outlooks and use them at least qualitatively.

When the very strong 1997-1998 El Niño occurred, attention was yet again refocused on climate and seasonal water supply issues (Pagano et al., 2000, 2001, and 2002). Comparisons between the 1997-1998 El Niño and the 1982-1983 event alarmed water and emergency managers. Forecasters responded with comprehensive statistical analysis of the historical impacts of El Niño (such as NRCS, 1997 and Brandon, 1998) and by adding climate indices to streamflow forecast equations where appropriate. Most significantly, the analyses revealed that there is not a reliable signal for El Niño in the Great Basin or the Upper Colorado River Basin above Lake Powell. While the 1983 event caused major flooding in this region, there are a greater number of counter-examples where El Niño did not bring wetter than average conditions. Research by the Bureau of Reclamation revealed an under-forecast bias for inflow to Lake Powell during El Niño years (Pagano et al., 1999). Perhaps this may be related to El Niño favoring cold April-June conditions in the Upper Colorado River basin (Pulwarty and Melis, 2001). If true, then a streamflow forecast based on snowpack alone would underestimate the observed flows because runoff efficiency is increased during cold springs. During spring 1998, water managers responded to public and political pressure to prevent a repeat of the 1983 event by releasing more water from their reservoirs than what would have been called for by using only the water supply outlooks. In the end, the water supply forecasts did underestimate the observed flow into Lake Powell, but not by an exceptional amount compared to previous years. Elsewhere, the forecasts accurately anticipated a wet season in Arizona and New Mexico and dry conditions in the Pacific Northwest.

In 1995, climate forecasts changed significantly, both in terms of their creation and methods of display. The format, which is still in use today, presents the forecasts as tercile probability anomalies for 13 overlapping 3-month forecast periods with lead times up to 1 year. While more information is presented using the current format, the methods for directly incorporating the climate forecasts have increased in complexity. In particular, disaggregating the overlapping 3-month periods into monthly values produces undesirable artificial "ringing" (Wilks, 2000). For example, a wetter than normal January-February-March forecast, followed by February-March-April and March-April-May climatology forecasts may counter-intuitively imply a drier than normal 1-month forecast for March. Although not statistically precise, Schneider and Garbrecht (2003) have developed an algebraic disaggregation that may be suitable for operational purposes. Briggs and Wilks (1996) addressed the issue of quantitatively translating precipitation probability anomalies into shifts in precipitation amounts. This methodology is conceptually similar to the underpinnings of the experimental "Probability of Exceedence" forecasts issued by CPC (Barnston et al., 2000). Garen (1998) and Modini (2000) attempted to ingest these "probability of exceedence"-style forecasts into the regression-based streamflow forecasting framework with mixed success. The procedure is complex, operationally intensive, and does not yield results significantly more accurate than simply using a climate index (e.g., SOI) directly as a predictor variable in a regression equation.

Another climate index of importance in western water supply, recently developed by Mantua et al. (1997), is the Pacific Decadal Oscillation (PDO). This index describes decadal-scale sea surface temperature variations in the north Pacific. Originally related to fluctuations in the salmon fishery, it has subsequently been shown that it has a modulating effect on the El Niño / La Niña climate signal. The phase of the PDO (cool or warm) has a significant effect on the strength of the relationship of the SOI with winter and spring streamflow in western Washington and Oregon, the relationship being much stronger during the cool phase than during the warm phase of the PDO (Koch and Fisher, 2000). By splitting the data record into cool-phase and warm-phase years, Koch and Fisher (2000) developed separate regression forecasting procedures to account for this effect. This method, however, has not yet found its way into operational forecasting, in part because of the difficulty in knowing the PDO phase in real-time. While PDO may excel at explaining long term variability in the historical record, the forecaster is left wondering which phase of the cycle is relevant to the impending streamflow forecast season (i.e. "Has the PDO shifted or not?"). Nonetheless, this topic is worth further investigation.

The most recent developments in the history of climate and western water supply forecasts are the 2001 La Niña and the ensuing Pacific Northwest drought. These events are discussed in later sections.

Operational Benefits

During and after the 1997-1998 El Niño event, and as a result of heightened interest in water management for the environment, there has been increasing pressure on operational agencies to issue longer-lead water supply outlooks. The general expectation is that these forecasts would be released in December or perhaps as early as September.

The skill in such forecasts would be low, but non-negligible. For example, Figure 1 shows the skill in using various predictor variables as a function of lead time for the Salmon River at Whitebird, a river in central Idaho that is relatively strongly influenced by El Niño. The authors hindcasted April-September streamflow from 1946-2001 using data available prior to various forecast "issue dates". The skill arising from El Niño (as shown by squares and measured by the Niño3.4 index) begins as early as June but flattens out by October, when the summer and fall state of El Niño, which is what most strongly affects winter precipitation, becomes known. Forecasts using persisted (i.e., previous months') streamflow (shown by circles) possess skill during the prior summer and become increasingly more skillful throughout the forecast season. Prior summer and fall streamflows are proxies for antecedent soil moisture conditions. Winter and spring streamflows reflect both antecedent soil moisture and winter low-elevation precipitation. Additionally, the authors derived a combined index of precipitation and snow (shown as triangles). Precipitation at Idaho City and McCall was used from June to December, and snow water equivalent at the Galena and Bear Basin sites was used after January. This information contains marginal skill in November that dramatically increases through the forecast season. The final dashed line shows the forecast skill when all variables are used together. Although the seasonality and magnitude of various skill components may change, this chart is qualitatively representative for many locations in the Pacific Northwest, Arizona, and New Mexico.

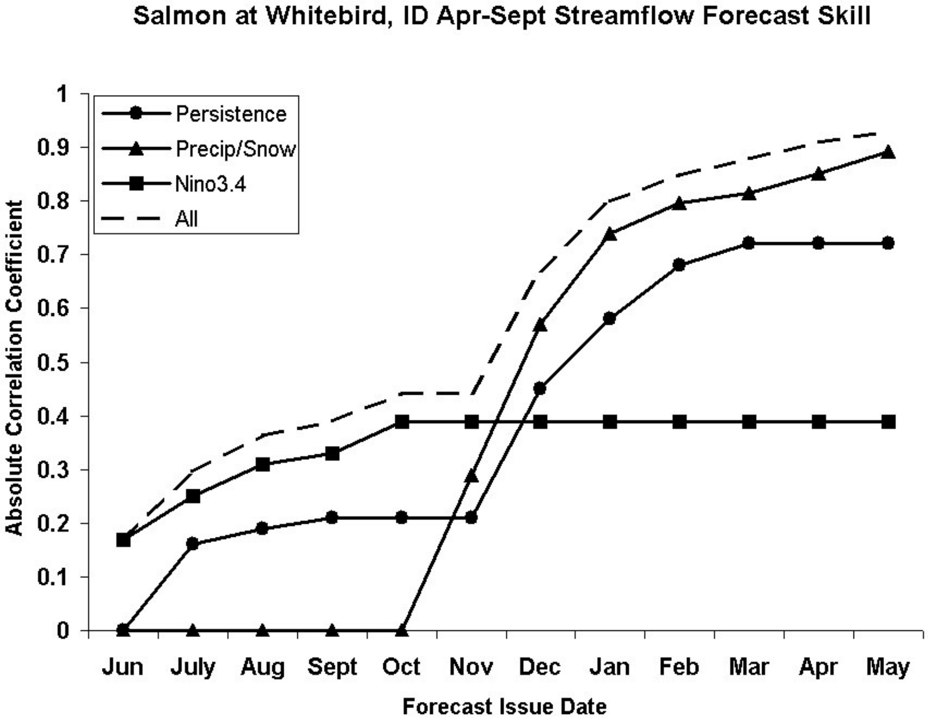

Figure 1. Progression of seasonal streamflow volume forecast skill versus issue date

To summarize, El Niño and soil moisture conditions contribute a low but still significant amount of skill to forecasts produced in June to November. Later in the season, snowpack is the best indication of the expected streamflow. It is not surprising that snow measurements have been the primary focus for water supply forecast agencies in the West. If agencies commit to producing early season hydrologic forecasts, however, proficiency in climate information, such as El Niño, is required.

"Climatologists are from Venus, Hydrologists are from Mars"

Figure 1 effectively illustrates a contrast between climate and snowmelt hydrology. The correlation between snowpack and streamflow is so strong that it is relatively easy to believe that the relationship is (almost) deterministic. By April 1st, an exceptionally heavy snowpack is virtually guaranteed to produce proportionately high streamflow, and similarly, low snowpack yields low streamflow. Before December or January, the hydrologist has little information "on the ground" upon which to base a forecast.

In contrast, the correlation between climate and streamflow is marginally significant, and one *must* think of the relationship probabilistically. While climate forecasters may find it loathsome to produce long-lead deterministic climate forecasts, many hydrologists fear that users might not accept a probabilistic streamflow forecast of this skill level, thinking that users would view them as "vague", "hedging", or "non-committal".

Hydrologists are also aware of the institutional barriers to using probabilistic forecasts. Many reservoir operating rules require a deterministic streamflow value. Water managers seeking to implement new dynamic operating procedures based on probabilistic forecasts encounter resistance from decades of tradition and external pressures to maintain consistency in operations. Such resource management, in the face of many highly conflicting interests, can result in rigid agreed-upon management practices, lest one party believe a new course of action is being taken at their expense to the benefit of others. Although some sophisticated water managers do consider risk and appreciate information about forecast uncertainty, a number of difficult challenges remain to those attempting to communicate probabilistic streamflow forecasts effectively. Some hydrologists would prefer not to issue a forecast that they suspect the user could not use or would misinterpret (Pielke Jr, 1999). The nature and scope of these challenges are explored further in the next section.

There is also a spatial scale contrast between climate forecasting and streamflow. The strong correlation between snowpack and streamflow requires close scrutiny of small spatial variations in snowpack when forecasting. As a result, hydrologists generally frown upon forecasting using snow measurements outside a basin's boundary. To the most extreme case, forecasters balk at using snow in central Arizona to forecast New Mexico streamflow although a weak correlation exists. Hydrologists lack knowledge about what new climate indices (e.g., the Arctic Oscillation, the Quasi Biennial Oscillation, Solar Cycles, etc.) are "in" their basin so that it makes sense to consider them when forecasting or which ones are "outside" of their basin and are spuriously correlated.

At the opposite end of the spectrum, climate forecasters typically focus on large-scale continental, if not global, patterns when making their forecasts. If the contours on a national forecast map match the observed contours, except that they are displaced, for example, 1000 km to the east, it is generally thought of as a successful forecast. If the connection between climate and streamflow is to be made, streamflow forecasters will need to think "bigger" and climate forecasters will need to think "smaller".

Cultivating skepticism, combating pessimism, retaining credibility

While very long-lead water supply forecasting requires proficiency in climate variability, it also demands expertise in probabilistic forecasts and concepts. Although nothing prevents the generation of short lead-time probabilistic forecasts, the uncertainty in long-lead forecasts brings the issue to a head.

The water supply forecaster who issues a highly uncertain probabilistic climate-based streamflow forecast should be prepared to engage users who demand that the forecaster "come clean" and tell them "what the forecaster *really* thinks is going to happen". This discussion is, of course, ill-framed because all forecasts are at their root probabilistic. Deterministic forecasts are probabilistic forecasts with zero error bounds (i.e. complete confidence). A deterministic forecast may also be some point along the probabilistic forecast distribution, arbitrarily chosen by the forecaster (e.g. the mean, median, or mode).

The danger in allowing the forecaster to choose the "one number" is that the internal risk model of the forecaster may be different from that of the user. Unless the forecaster is intimately familiar with the user's operations, the forecaster is not qualified to judge what level of risk the user should accept. It is not the role of the forecaster to determine if and how water managers should use probabilistic forecasts to manage risk. Ultimately, the forecaster's efforts should be focused on quantifying and issuing the most unbiased, informative, and useful forecast possible (as discussed by Murphy, 1993).

While the scientific literature has repeatedly shown that probabilistic forecasts are more appropriate and articulate than deterministic forecasts, the authors recognize the rift within the operational community concerning the perceived low user demand for probabilistic forecasts and their inability to interpret them. In a recent case, a southwestern water manager, the Salt River Project, commissioned the development of an advanced climate-based water supply forecasting tool, but the user then developed a post-processor to convert the probabilistic output into a deterministic forecast.

If confronted with a user demanding a deterministic forecast, the hydrologist should consider if the user, in asking for the uncertainty to be removed from the forecast, tacitly wants the uncertainty to be removed from nature. After all, given enough time, money, satellites, and climate indices, one should be able to come up with the perfect forecast. The user, dissatisfied with the agency forecasts' large uncertainty, may seek out alternate opinions among, for example, the outputs of individual forecast tools or private consultants.

While it can be difficult to distinguish this user from the sophisticated user who accesses as much information as possible to supplement the official forecast, the former may suffer from "confirmation bias". This is a type of natural selective thinking encountered in a variety of contexts whereby one tends to notice and to look for what confirms one's beliefs and to ignore, not look for, or undervalue the relevance of contradictory evidence (Kahneman et al., 1982). The most dangerous combination is a user with a confirmation bias who relies upon forecasters who suffer from their own form of confirmation bias and who thus are willing to "go out on a limb" to attract customers with very confident (and thus presumably skillful) forecasts. When this water manager uses a "one number" deterministic forecast, which then greatly differs from the observed, the user is likely to foist responsibility for any negative outcome back onto the forecaster who presumably "read the signals wrong" or did not try hard enough.

Some operational water supply forecasters are skeptical of climate forecasts, often because of an instance in which the individual put faith in a climate outlook, and this resulted in undesirable consequences and regret. In one notable instance, in the fall of 2000, a strong La Niña was underway, combined with the cool phase of the Pacific Decadal Oscillation (PDO). These phenomena together provided the strongest possible climate-based indication that the Pacific Northwest would be wetter than average in 2001. For example, at the time, the driest of the other nine La Niña/cool PDO years since 1936 on the North Fork Flathead River near Columbia Falls (Montana) had April-September streamflow almost exactly 100% of average; the wettest year on record, 1974, at over 160% of average, was a La Niña/cool PDO year.

For a variety of subjective reasons, the NRCS did not issue any early season forecasts in the fall of 2000. In the end, 2001 tied or broke records for the driest year on record in the Pacific Northwest, contrary to the climate forecast guidance. The North Fork Flathead experienced its third driest year on record at close to 50% of average flow. In retrospect, water supply forecasters felt that they had "dodged a bullet" by ignoring the climate forecasts. Many streamflow forecasters have a "What about 2001?" anecdote readily available as a justification as to why they do not rely on climate forecasts more heavily.

Forecasters and users alike must accept that, since the relationship between streamflow and climate is probabilistic, "No one can win them all." The threat of having a forecast "bust", however, strikes fear into all but the most steeled hydrologists. As Lewitt (1995) describes this situation: "[The event is not] entirely predictable, though it is possible to calculate the ranges of probability. Still, in every range there is the one in a billion chance, the blind shot that seems so improbable that we ordinarily discount it. And when it does happen, our sense of fair play is often more injured than our actual conditions." Who accepts responsibility when nature does not obey the predictions – the climate forecaster, the hydrologist, or the user? Given sufficiently negative consequences, even a long record of appropriate decisions can be negated by a single "bad" decision. Over the long term, however, if the climate information is properly used, the streamflow forecasts should improve in general.

While important, the Pacific Northwest example should not be overstated. At the opposite end of the spectrum from the user trying to strip nature of its uncertainty is the one who believes that long range predictability is impossible. One might encounter a hydrologist who perceives that "making a streamflow forecast in September, before any snow has accumulated, amounts to swinging before the ball has been pitched. One is bound to strike out.” Such hydrologists may feel *Schadenfreude* (malicious joy) when a forecast disagrees with the observed because it confirms their negative impressions of climate forecasts and releases them from any need to change their current operations. A forecast user may adopt the same mis-perspective that if the future is completely uncertain, there is no need to deviate from business as usual. Even if a catastrophic event occurs, such users feel absolved of responsibility, as the disaster was an unforeseeable “Act of God”. The use of fixed reservoir operating “rule curves” operates under the principle of minimizing risk in the face of complete future uncertainty. The reality of climate forecasts lies somewhere in between the extremes of complete uncertainty and complete predictability.

One key to interpreting and using probabilistic forecasts is to have a clear quantitative understanding of forecast uncertainty. Often, users have only a subjective notion of how close the observed ought to be to the forecast to consider it acceptable. If the observed deviates too far from this subjective tolerance, then the user denotes this forecast as a “bust”. Whether a forecast is a “bust” or not, however, depends on whether the observed lies outside reasonable error bounds, which themselves depend on the forecast uncertainty. Users must be fully cognizant of this interrelationship to understand the magnitude of possible deviations of observed from forecast. In the end, there are no “bad” probabilistic forecasts, only unlikely outcomes.

A second key to understanding and using probabilistic forecasts is to realize that the chance of the observed ever equaling the deterministic forecast is essentially zero. Even under the best circumstances, one will always observe more or less than the forecast quantity, with probabilities described by the error distribution. Once this is understood, users can then develop, and when necessary implement, contingency plans in the event that more or less water is received than the forecast. This is true regardless of the chosen exceedance probability of the forecast quantity. Difficulties can arise if users and managers base their plans only on a single forecast quantity, ignoring the possibilities described by the forecast distribution. The danger in interpreting the “one number” forecast as “destiny” is particularly serious when involving long-range climate-based streamflow forecasts because the likely error is much higher than late-season snow-based forecasts.

Practical Advice to Water Supply Forecasters

Climate forecasts have long represented an opportunity to improve seasonal water supply forecasts. For decades, however, climate forecasts have been perceived as having insufficient skill and specificity for use in the operational hydrology environment. While climate forecasts may not significantly improve water supply outlooks during the snowmelt period, they possess great strength in providing information prior to snowpack accumulation, as early as September. While these pre-season forecasts are highly uncertain, they remain an improvement over the next best alternative (i.e., no information at all).

Although some technical barriers to incorporating climate outlooks into the water supply forecasts exist, the primary challenge is a perceptual barrier. To utilize such highly uncertain climate information properly, forecasters and users both must understand water supply forecasts in probabilistic (rather than deterministic) terms. Regrettably, operational hydrologic, climate, and weather forecasters have struggled for decades to communicate forecast uncertainty effectively (O’Grady and Shabman, 1990; Sarewitz et al., 2000). Some progress has been made, particularly in the past decade or so, in the tabular and graphical display of forecasts to communicate more clearly the probabilistic nature of the forecasts. Continued efforts along these lines in both the academic and operational communities are needed.

While it is outside of the scope of this paper to determine if water managers should use long-lead yet uncertain climate-based water supply forecasts, it is safe to say that operational forecast agencies will inevitably start issuing them. Water supply forecasts were originally issued first in April, with March forecasts beginning in the 1950s, February forecasts in the mid-1960s and January forecasts in 1980. The historical trend towards longer lead-time forecasts suggests that the advent of December (or earlier) forecasts is overdue. The question remains not whether but how best to implement this system.

Operational forecast environments typically have several forecasters, each responsible for a limited subset of basins within the office's larger forecast area. At least one of these forecasters should have good to excellent proficiency in interannual climate variability, with a working knowledge of the tools used by the official climate forecasters at the Climate Prediction Center (CPC). During the forecast season this individual is encouraged to monitor and/or participate in the forecast development teleconferences CPC holds. This hydrologist can then brief the other hydrologists on the climate outlook, field questions about the forecast and develop a collective strategy on the implications for local streamflow. It might be possible for the climate-savvy forecaster to develop the pre-season forecast for all areas, alone, with subjective input from the other hydrologists.

This forecaster should be able to provide practical advice on using climate information in forecast equation development. For example, climate signals are typically large scale in nature (e.g., larger than 500 km across) except in coastal regions where the effects can be isolated. Therefore, if no streams in a region are correlated with climate except one, the correlation is likely spurious. Climate phenomena typically contain much persistence from month to month, and their high frequency variability usually does not contain relevant information. Therefore, exhaustive analysis of every combination of months of a climate index to find the optimal combination for forecasting (i.e. "Hunting and Pecking") results only in over-fitting. Three-month averages (such as September-November) of climate indices should suffice. Also, one should choose only climate indices that will be available at forecast time; currently the Southern Oscillation Index is operationally supported, whereas the Pacific Decadal Oscillation is updated irregularly by an academic institution.

Each office within the water supply forecast environment would benefit from an individual also proficient in advanced statistics and probability concepts as well as someone with an interest in visual display and communication of uncertain information. These members can develop a regionally appropriate strategy for emphasizing forecast uncertainty without overly discouraging users. They can also address whether early-season forecasts require a fundamentally different format from those issued throughout the regular season. Depending on availability, the agency may partner with the local NOAA Regional Integrated Sciences and Assessments project to serve as a user liaison. These projects have the interest and resources to develop and quantitatively test alternative forecast delivery formats. All forecasters should have a working knowledge of basic statistics and probability concepts; popularly accessible works such as Bernstein (1998), Gilovich (1993), Kahneman et al. (1982), Plous (1993), or Pollack (2003) can also assist in giving forecasters basic non-technical tools and concepts to help communicate forecast uncertainty to users.

The forecast environment should already be capable of historical forecast archival for the evaluation of forecast accuracy. There is no reason why this system cannot also include more uncertain, early season climate-based forecasts. Retrospective evaluations can measure the relative improvements of using climate information over existing practices. Hindcasting and simulated forecasting exercises (such as Baldwin et al. [this volume]) can help streamflow forecasters build realistic expectations (that is, not overly inflated nor unnecessarily pessimistic) of what will occur when using climate forecasts. If effective, there is a good chance that the climate forecasts will be properly applied, without regrets.

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