Variable Infiltration Capacity (VIC) Model

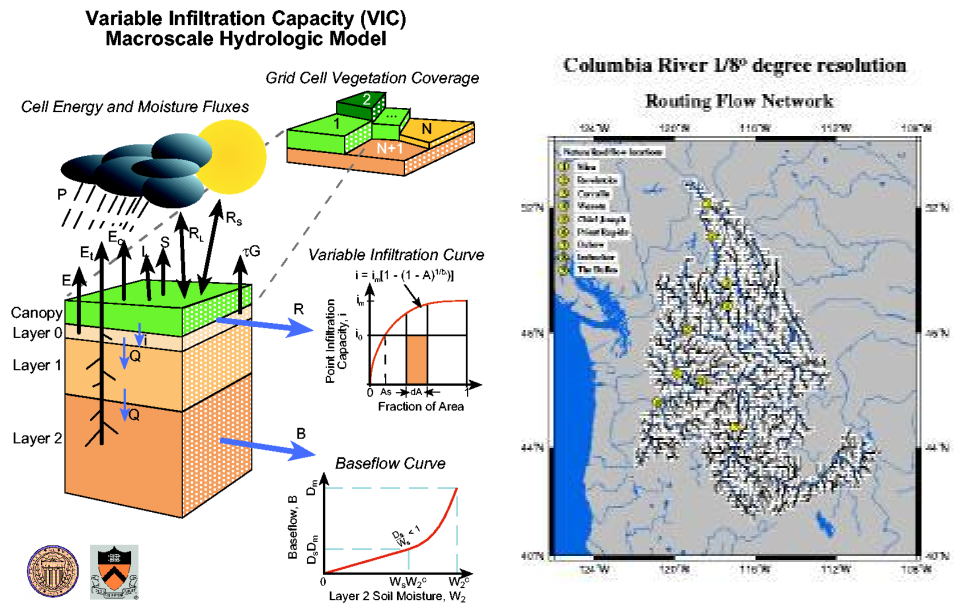

Figure 2 Schematic of the land surface scheme in the VIC hydrologic model and the simulated channel network for the Columbia River at 1/8th degree resolution

VIC does not simulate hydrologic processes associated with groundwater or groundwater/surface water interactions. Thus the changes simulated by the model are associated only with changes in surface water processes. In areas where significant interactions between ground water and surface water are present (and could potentially be altered by changes in climate), these scenarios should be used with a clear understanding of their limitations. The adjustments to the historic streamflow record we employ here assume that the groundwater component of the observed streamflows remains constant with time.

The hydrologic scenarios are produced by perturbing the historical meteorological driving data for the hydrologic model (based on the changes in precipitation and temperature predicted for each climate change scenario) and then running the hydrologic model for this altered climate. Thus an altered version of the historic streamflow record is produced, which may be compared with the historic streamflow record for the current climate in a planning context.

Although the VIC hydrologic model successfully captures many important features of PNW hydrologic variability, like all hydrologic models, the model output is sometimes biased in comparison with naturalized observations, and also contains random errors associated with errors in the driving data, uncertainties in parameter estimation during calibration, etc. Although these kinds of systematic errors are often secondary to the problem at hand, in practice hydrologic model bias can create difficulties when using simulated streamflow data in a water planning study, because a direct comparison of results derived from the historic streamflow record may yield "apples and oranges" comparisons that are difficult to interpret. Bias correction techniques can largely eliminate these kinds of problems without significantly distorting the important physically-based signals produced by the hydrologic model.

Bias Correction Techniques
The simplest kind of bias correction corrects for a systematic discrepancy in the mean by "rescaling" the mean of the simulations to match the observations. Similarly, a discrepancy between the variance of the simulations and the observations can be corrected by assuming a probability distribution (such as the normal distribution) and mapping normalized anomalies (i.e. standard deviations from the mean) between the simulated and observed populations. In many cases, however, the true form of the probability distributions of the simulated and observed data are not known with any certainty and the two probability

distributions are not necessarily of the same form or statistically well behaved. In these cases a "quantile-based" bias correction scheme can be used to "translate" between the simulated and observed populations (see Wood *et al*., 2002). In this technique, simulated and observed data covering the same period of record are used to create a "quantile map" of each population using an unbiased quantile estimator (e.g. after Cunane in Maidment *et al*., 1993) applied to ranked data. Figure 3 shows the sequence of steps in extracting a bias corrected value from a simulated value using a quantile-based bias correction scheme. A simulated value is the input to the process and is associated with a particular quantile in the simulated distribution (i.e. the simulated value to be bias corrected is associated with the Xth percentile in the simulated distribution). This same percentile is extracted from observed distribution (i.e. the Xth percentile in the observed distribution is identified) and this quantile in the observed distribution becomes the bias corrected value.

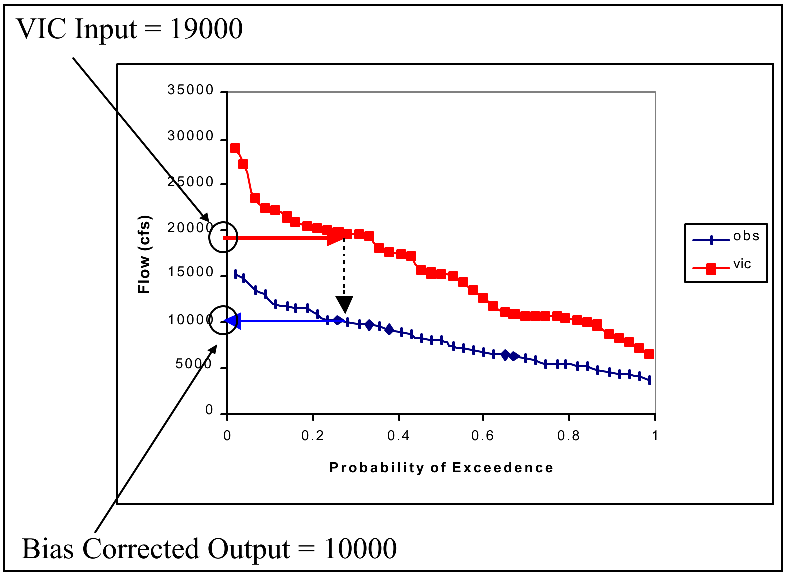

Figure 3 Illustration of quantile-based bias correction scheme (after Wood *et al.* 2001)

If the simulated values to be bias corrected come from the same population as the simulated training data, it is expected that this bias correction scheme will tend to translate the simulated data so that the probability distribution of the bias corrected values closely resembles that of the observed training data. If a group of simulated values have a particular "signal" contained within them, the translation process will tend to reproduce in the output the signals present in the input. An extremely wet hydrologic simulation, for example, will always map to an extremely wet observed value. As long as the fundamental physical processes that define the quantile map for the simulations are not significantly altered over time and the simulations capture the essential signals accounting for variability, the bias correction scheme should produce a reasonably undistorted "image" of the raw simulated data in the observed space. Figure 4, for example, shows bias corrected streamflows for the Columbia River at The Dalles, OR for WY 1991-1996, using quantile maps created using data from WY 1950-1989. Note that the training data for the bias correction process and the test data are independent in this example.

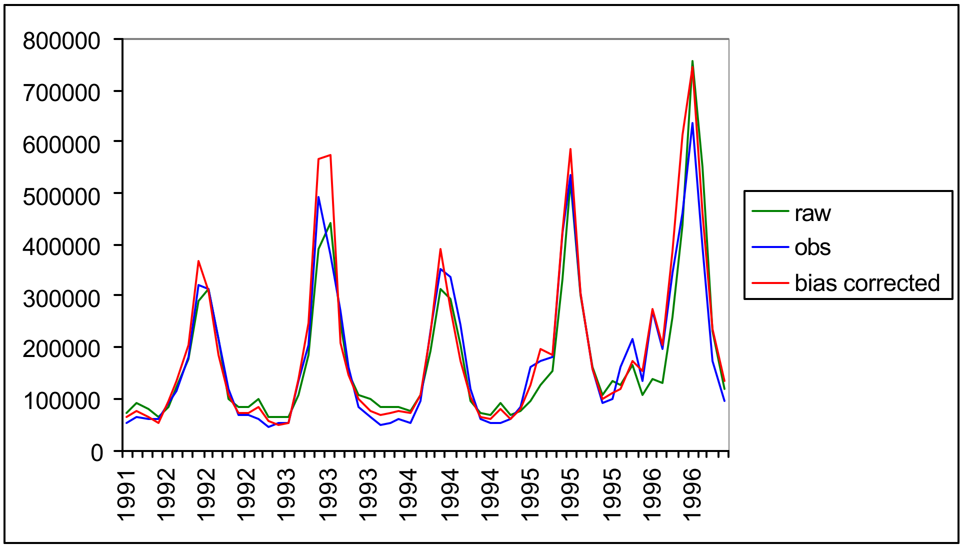

Figure 4 Bias corrected simulated streamflows for WY 1991-1996 compared to naturalized observations for the (Columbia River at The Dalles, OR).

Note also that there are errors in the hydrologic simulations that are not associated with systematic model bias. The discrepancy in observed and simulated peak flows for WY 1993, for example, are probably attributable to spatial errors in precipitation data. These kinds of errors in individual months of particular water years are largely removed by the final step of the data processing sequence described below.

In the context of simulating climate change streamflow scenarios, several other potentially important problems emerge that are not present in bias correcting simulations of the "current climate" described in the preceding paragraphs. Firstly, the simulated value may be outside the range of the simulated quantile map. It is straight-forward to extend the simulated and observed quantile maps with a fitted distribution, and this theoretical distribution can be used if the simulated values are not too far outside the range of "current climate" simulations. For values far outside the range of simulations for the current climate (which can occur because of shifts in streamflow timing), the "observed" quantile maps for the climate change scenario are not known, and a very simple rescaling procedure based on the long term mean is probably as effective as any other technique (and is used here). Figure 5 shows the decision tree used in this study for selecting the primary bias correction technique.

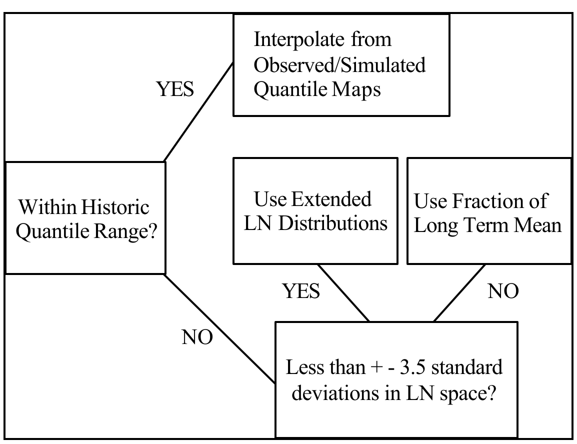

Figure 5 Decision tree for selecting the primary bias correction scheme for the hydrologic model output

The second problem that can occur is that in the process of bias correcting individual months, annual streamflows (which hydrologic models usually simulate quite well) may be distorted. For example, in a climate change simulation, the bias corrected annual mean flow may be 75% of the current climate values for the same year, but the sum of all the monthly bias corrected values may be 80% of the current climate values. To remove this artifact of the monthly bias correction process, each month of the bias corrected simulation ("bc_climate_change" in the equation below) is multiplied by rescaling factor F defined by:

$$(\text{bc\_annual\_mean\_flow})*12 = (\Sigma\ \text{bc\_monthly\_flow}) * F$$

Thus the bias corrected annual streamflow is exactly reproduced by the rescaled monthly values, but the relative "shape" of the monthly values is defined by the monthly quantile mapping procedure. The correction factor F is usually close to 1.0, so the monthly values are not greatly distorted by this procedure.

A similar problem to that described above can create discrepancies in spatial mass balance at an annual time scale as well. This can occur because each streamflow location is bias corrected independently. To deal with this issue, mass balance is checked starting from the most downstream location and working upstream, and the sum of the upstream sites are then adjusted to exactly equal the downstream flows on an annual basis. Figure 6 shows the four components of the mass balance adjustment for The Dalles (1), Priest Rapids (2), and Ice Harbor (3) in the Columbia River basin. Note the addition of the incremental inflow (which is also bias corrected) to close the water balance equation.

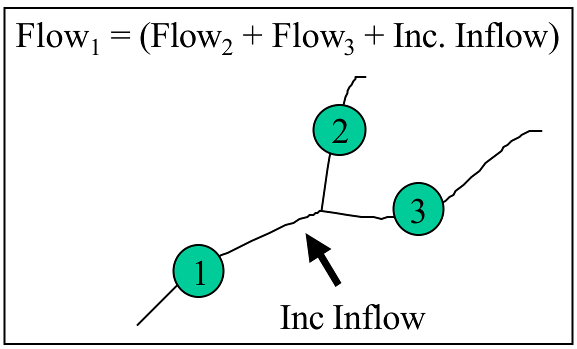

Figure 6 Schematic for mass balance correction in the bias correction scheme

Final Adjustment of Historic Streamflow Record
After hydrologic simulations for both the current climate and the climate change scenario are bias corrected, a time series adjustment to the historic streamflow record is calculated as the difference between the climate change simulation and current climate simulation (i.e. climate change minus currrent climate for each month). This adjustment is simply added to the historic record for each month, which is aligned in time with the simulations. This final step tends to minimize the importance of errors in the hydrologic model simulations for particular months due to errors in driving data, etc. The final product covers only the overlapping period between the historic record and the hydrologic simulations, and consists of an observed naturalized streamflow sequence, and an adjusted record for the same period representing the altered climate. For the pilot project this overlapping period is WY 1950-1989.

Thus the bias correction process has five steps:
1) Quantile mapping between simulated and observed space for each month in the water year
2) Quantile mapping between simulated and observed space for annual mean flow
3) Adjustment of monthly flows to match bias corrected annual values
4) Adjustment of flows at different locations in the channel network to preserve mass balance, moving from the downstream most site to the upstream sites.
5) Application of changes in the bias corrected simulated streamflows to an overlapping period of the historic record.

Figure 7 shows a monthly summary of the VIC simulations before and after bias correction. Note that despite considerable differences between the raw and bias corrected simulations, the climate change signals present in the raw simulations are preserved.