Puget Sound Bucket Model

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1. Overview

To assist with understanding the causes of salinity anomalies within Puget Sound, we have developed a simple one-layer salt conservation model that can be compared against observed salinity variations within various Puget Sound basins. As the only time-variable input to this model is USGS river flow measurements, correlations between the model and observations give some indication of how much a particular anomaly may be associated with regional freshwater changes. Specifically, a high correlation suggests that salinity changes are due to local changes in river flow, which is linked to both meltwater and regional rainfall. The model presently does not use estimates of evaporation rates, which would offset freshwater inputs but would likely be a small term except possibly during the summer. It is important to recognize that although high correlations *suggest* that salinity changes are due to local changes in freshwater input, they do not definitively attribute *causation*. For example, changes in salinity at the boundary of the basin, say due to a reduction in the Fraser River flow, could follow a similar pattern to local river flow variability. Some of the change in local salinity could be due to this boundary change and not local freshwater input changes even though the model-observations correlation is high. That said, because of the long-term stability of the model skill at such places as South Sound (a decade) and the fact that the model output is based on simple salt conservation using real-world numbers with minimal tuning, high correlation is a strong argument for causality.

2. The Model Framework

The model is based on simple salt conservation for a particular basin. First starting with the definition of salinity:

$$S_{ppt} = \frac{M_S}{M_S + M_{FW}} \tag{1}$$

where salinity in parts per thousand (S_{ppt}) is equal to the mass of salt (M_S) divided by the total of the mass of salt plus the mass of freshwater ($M_S + M_{FW}$). In model calculations we use units of kilograms.

We add time variability to this simple balance with terms describing the flux of salt (in kg/s) into and out of a particular volume. This volume is the average water volume of a particular Puget Sound basin, assumed to remain relatively constant over periods greater than the dominant tidal periods (∼24 hrs). So, the time-varying salt budget of a particular basin is:

$$S(t)_{ppt} = \frac{M_S(0) + \Phi_S(t)_{net}}{M_S(0) + M_{FW} + \Phi_S(t)_{net}}, \tag{2}$$

where $\Phi_S(t)_{net}$ is the time-integrated *net* salt flux into the basin and $S(t)_{ppt}$ is now the time-variable salinity in ppt. $M_S(0)$ is the initial salt mass within the basin and the mass of freshwater (M_{FW}) in the basin remains constant as the volume doesn't change.

The net time-integrated salt flux term (in kg) can be broken down into that flowing into the basin and that flowing out:

$$\Phi_S(t)_{net} = \int_0^n F_S(t)_{in} \partial t - \int_0^n F_S(t)_{out} \partial t. \tag{3}$$

Considering that the subtidal, estuarine density-driven flow into a basin will be roughly proportional to the difference in salinity between the basin water and the boundary conditions, we formulate a simple relationship for $F_S(t)_{in}$ of:

$$F_S(t)_{in} = [S_B - S(t)]M_{in} = [S_B - S(t)]Q_{in}\rho, \tag{4}$$

where S_B is a *constant* boundary condition salinity and M_{in} is the mass flux (units in kg/s) of oceanic inflow into the basin and is equal to the inflow volume flux times the density of inflow water, or $Q_{in}\rho$. The form of this approximation is important in that it acts as a brake on salinity increases. If basin salinity exceeds that of the boundary conditions, then the sign of this flux reverses and salt moves out of the basin. As will be shown, this form is taken from the balanced Kundsen relation that combines conservation of salt and volume.

The time-variability of the model is introduced in the $F_S(t)_{out}$ term, such that:

$$F_S(t)_{out} = AM_R(t)S(t) \tag{5}$$

where $M_R(t)$ is the USGS river discharge in units of kg/s and A is a scale factor greater than one to account for unmeasured basin freshwater inputs that co-vary with this river flow. Here we're assuming homogenous vertical mixing so that the water moving out of the basin has the depth-averaged salinity of the basin.

This model has a form that is similar to the time-dependent Knudsen relationship. In the classic formulation, invoking conservation of volume, the net volume transport out of a basin is the inflow plus the river flow:

$$Q_{out} = Q_{in} + Q_r. \tag{6}$$

Now, if the salinity on some timescales is relatively constant in a basin, then "salt in" needs to equal "salt out". For salt fluxes this is:

$$S_{in}Q_{in} = S_{out}Q_{out} \tag{7}$$

now substituting,

$$Q_r S_{out} = Q_{in}(S_{in} - S_{out}). \tag{8}$$

The two sides of the above equation are the basis for our two varying salt flux terms, $F_S(t)_{out}$ (l.h.s) and $F_S(t)_{in}$ (r.h.s). However, for a time-varying solution these two terms cannot be in balance. Using a Q_{in} that is constant or possibly proportional to $S_{in} - S_{out}$ allows us to separate it from the flux associated with river discharge, creating an imbalance that changes basin salinity in time.

There are three tunable parameters in this model, although all three can be somewhat constrained by reality (or observations). First, there is the scale factor, A, that is used to estimate the non-measured freshwater flow into a particular basin. For South Sound, for example, this is set to 1.8 times the measured Nisqually River flow. This takes into account local rainfall runoff, rain directly falling on the water, groundwater, un-measured streams. It also may adjust for some averaged evaporation rate. Secondly, as the volume flux into the basin is unknown, this is a parameter that can be tuned. Lastly the salinity of the inflowing water, S_B (or S_{in}), which is important for limiting the largest values of S in the model, can also be adjusted. Note that both the boundary condition salinity and the volume flux are in the same salt-flux-in term, but changes to each influences the model results in subtly different ways.

The three parameters are adjusted for each basin, using an iteration method that maximizes the correlation of a linear-regression with the depth-averaged salinity of a particular basin as measured by an ORCA mooring (e.g. Carr Inlet Buoy for South Sound).

Differences between model and this depth-averaged salinity can be attributed to a number of factors, including:

- errors in the estimate of the flux of salt into the basin
- errors in the estimate of the flux of salt out of the basin (related to item below)
- time changes in the scale-factor (A) relating river flow observations to total basin freshwater input.
- data gaps or errors in the USGS observations
- non-representativeness of the ORCA mooring observations w.r.t. basin salinity changes.
- break-down of the assumption of a depth-averaged salinity (e.g. very shallow fresh outflow that does not influence deeper water).