Appendix M.
Residence and Flushing Times

This appendix describes the residence and flushing times for the various basins in Greater Puget Sound. For definitions of terms, including statistical performance metrics, refer to the glossary in the main report.

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Residence and flushing times in various regions of the Salish Sea

Residence vs. Flushing Times

The differences between residence and flushing times can be confusing, and different authors use slightly different definitions and approaches. Residence time is a local measure of the length of time that a particular water parcel remains within a water body, while flushing time is an integrative measure of the time required to replace the entire volume of water within a water body. If the particular volume of water studied is of exactly the same size as the entire water body, residence time and flushing time will be the same.

In this study, we define residence and flushing times based on virtual dye experiments. For example, for a water body that is defined by ten different parcels of particular volumes each, the residence times of each parcel will be different and will be equal to the time taken for the initial concentration of the virtual dye in each of the ten parcels to reach a threshold. On the other hand, flushing time is a bulk measure of the time taken by the volume-weighted average concentration of the virtual dye in the whole water body to reach a threshold.

In an estuary as complex as Puget Sound, the volume of embayment and exchange flows to and from them are variable, and the system has difficulty completely flushing out. Therefore, alternative approaches are needed to quantify residence and flushing times within the Salish Sea. Premathilake and Khangaonkar (2022) define residence time as the time it takes for a water parcel to leave its embayment of origin through a designated domain boundary. In contrast, they and others define flushing time as the time to replenish all the water in an embayment with exchange flow through the open boundaries of that embayment (Premathilake and Khangaonkar 2022; MacCready et al. 2021).

Longer residence times promote stagnation and buildup of pollutant concentrations, increase primary productivity and depletion of nutrients, increase nitrification (oxidation of ammonia to nitrate, which depletes oxygen), increase settling of particulate organic matter (i.e., dead algae), and increase decomposition of organic carbon (which depletes oxygen). Higher residence times are indicative of where the potential hot spots are for biogeochemical stressors.

Characterizing estuarine time scales as an e-folding time

Following Monsen et al. (2002), we define the flushing time as the time required to reduce the concentration of a virtual dye to 37% (=1/e) of its original value within a water body. This is also referred to as the e-folding time, as the denominator in the 1/e is Euler’s number (2.71828). Premathilake and Khangaonkar 2022 defined this flushing time as Eulerian Flushing times (EFT), which was similarly calculated as the time taken for the spatially average dye concentration for the selected embayment to reach 1/e fraction of its initial concentration. We recognize that the estuarine residence times are both spatially and temporally variable (Oliveira and Baptista 1997) and that these are going to be different during low summer flows and high winter flows (Hetland and Geyer 2004).

In this study we estimated the residence times for each grid cell within a region as well as the flushing times for the whole region within the Salish Sea, by introducing a virtual dye at time zero (January 1st) in a specific region and allowed the dye to escape and reenter at the boundary in each experiment. The residence times show how long the dye remains in a grid cell, while flushing times estimate the average time the dye remains in a basin made up of many cells. We recognize that the initial dye introduced at the start of a different season of the year would result in different residence and flushing times.

This approach is similar to recent studies in which e-folding times were used to estimate estuarine timescales within the Salish Sea. Using results from a two-layer box model, MacCready et al. (2021) computed tracer-based e-folding times using exchange flows computed from the three-dimensional Regional Ocean Modeling System (ROMS) model and allowing for reflux at the open boundary. These values, which MacCready et al. (2021) called T_{res}, could be considered analogous to the EFT values that Premathilake and Khangaonkar (2022) estimated. MacCready et al. (2021) also computed a separate time metric that did not include reflux considerations and computed it as the volume of the box divided by the water flux through the volume (V/Q). MacCready et al. (2021) emphasized the importance of reflux considerations since the V/Q values were reported to be shorter than the former (T_{res}). Ahmed et al. (2017) also computed tracer-based e-folding times using a structured three-dimensional grid using the Generalized Environmental Modeling System for Surface Waters (GEMSS) for South and Central Puget Sound. Although a different model of the region, the procedure of estimating e-folding times was similar to the other two studies.

Knudsen-based index compared to e-folding times

Ahmed et al. (2019) reprinted a residence time indices plot (Albertson et al. 2016) for the central portion of the Main Basin, in which 2006 had the highest index compared to the indices for 2008 and 2014 (Figure M-1). Those residence time indices were estimated by a Knudsen relationship using a salt-balance approach (Burchard et al. 2018) using river flow and observational marine data for the upper 30 meters for the period of May through August (Albertson et al. 2016). Residence time is displayed as an index relative to a 16-year baseline.

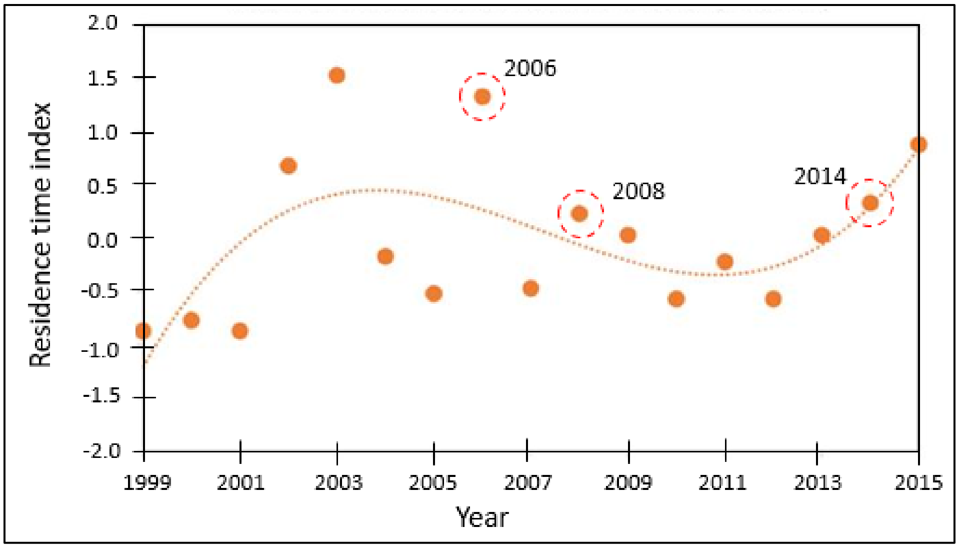

Figure M-1. Index of residence time relative to normal in the top 0 – 30 m in Central Puget Sound, 1999 – 2015 (Albertson et al. 2016).

Estuarine circulation is primarily influenced by interactions between freshwater discharged from rivers and tidal mixing, with other factors like wind and bathymetry also playing a role. Low freshwater flows result in reduced estuarine circulation and enhanced residence and flushing times. Ahmed et al. (2019) pointed out that Fraser River had the lowest annual average flows in 2006 compared with 2008 and 2014. However, within Puget Sound, annual average flows were lowest in 2008 for the Skagit, Stillaguamish, Nisqually, and Skokomish rivers.

Ahmed et al. (2019) presented the residence times, represented by e-folding times, at the intermediate scale grid level (Figure M-2, the red colored region) after introducing a virtual dye tracer throughout the model domain at the beginning of each model simulation. This simulation used the Puget Sound Model (PSM) with open boundaries at the mouth of the Strait of Juan De Fuca and the middle of the Strait of Georgia, and tracer dye was not allowed to re-enter into the model domain once it crossed the open boundaries. On a qualitative basis (Figure M-3), residence times were generally longer for the year 2006, with e-folding times in Penn Cove (red circles in Figure M-3) longest in 2006 (approximately 270 days) compared to those in years 2008 and 2014 (approximately 250 days and 170 days, respectively).

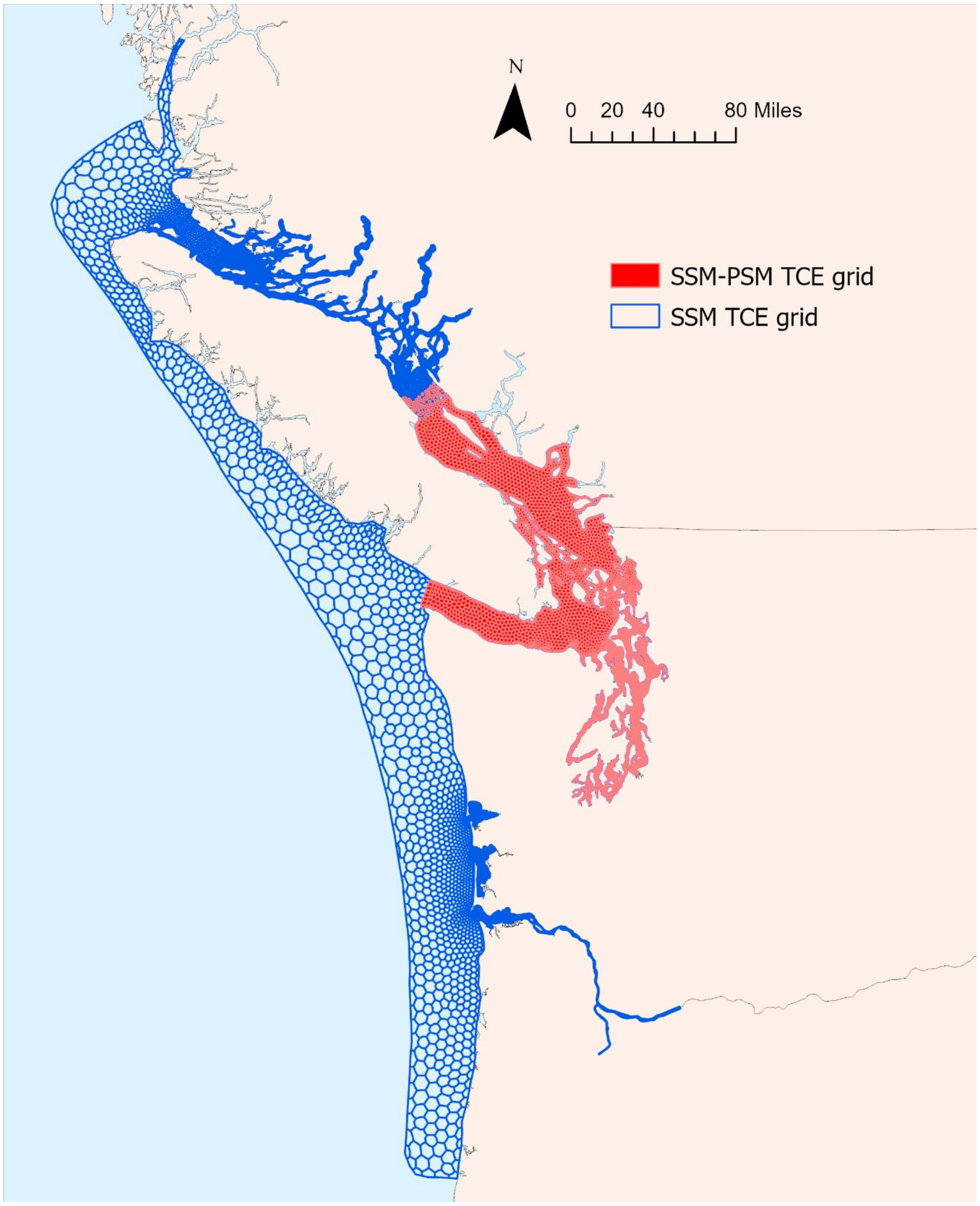

Figure M-2. The Salish Sea Model domain (blue + red) and the PSM model domain (red).

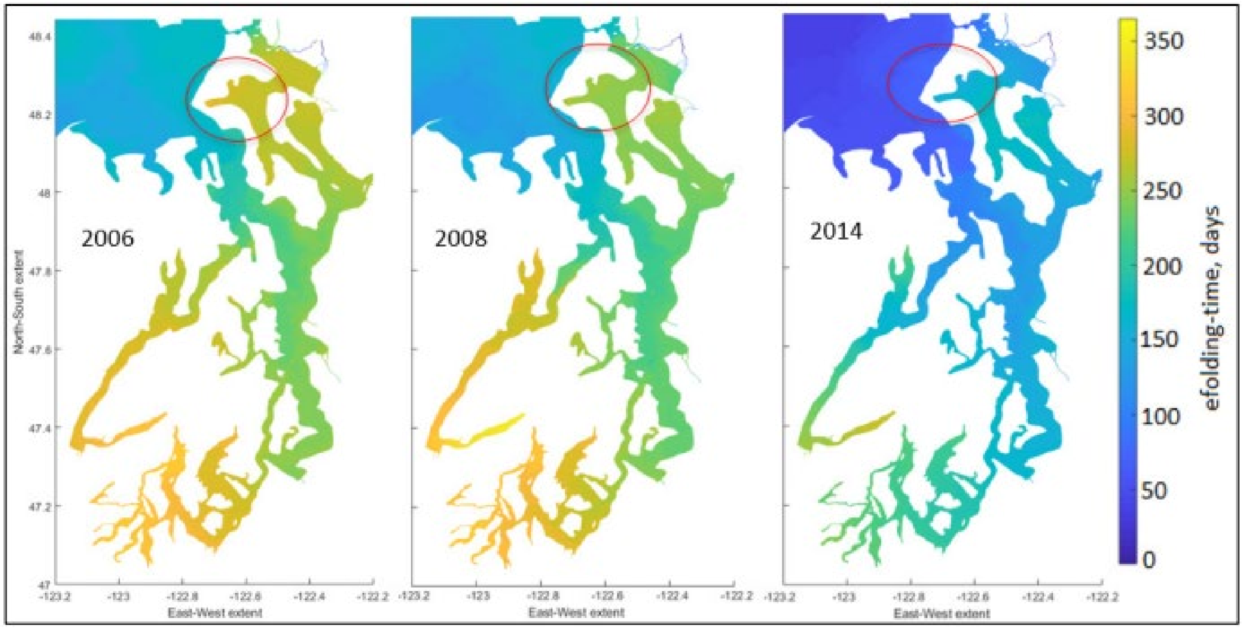

Figure M-3. Cell e-folding times using the PSM model, reproduced from Ahmed et al. (2019).

In this report, we present the residence times using the same intermediate scale but expanded Salish Sea Model domain, which extends beyond the entrance of the Strait of Juan de Fuca, into the continental shelf and beyond the Georgia Strait into Queen Charlotte Sound (Figure M-2). The residence times were calculated as e-folding time by introducing an initial tracer dye concentration within the red region in Figure M-2 on January 1st. Model runs were conducted for years 2000, 2006, 2008, and 2014 to calculate e-folding times for all locations and for all four years. Note that in this simulation, the open boundary for the dye is well within the SSM model domain, so the dye is allowed to reenter the dyed region. Initial concentrations outside of the dyed region are set to zero but are allowed to increase as dye from the dyed region transports out. These simulations used the updated watershed delineations and flows as described in Appendix B.

Planview maps showing e-folding times for this study are presented in Figure M-4 with initial dye in the PSM extent of the Salish Sea Model for years 2000, 2006, 2008, and 2014. The color scheme is kept the same as that in Ahmed et al. (2019). Within Puget Sound, the longest residence times are in locations furthest from the open boundary of the initial dye region. The residence times in locations within Hood Canal and South Sound finger Inlets are in the order of 300 days or more for all the years modeled. This indicates the tendency of waters within the greater Puget Sound to recirculate or reflux within the estuary and remain there long-term, particularly within the southernmost terminal embayment. Khangaonkar et al. (2017), using the same intermediate scale expanded SSM model for 2006, found that 58% of the surface outflow was refluxed back to the lower layers at Admiralty Inlet, flowing inland.

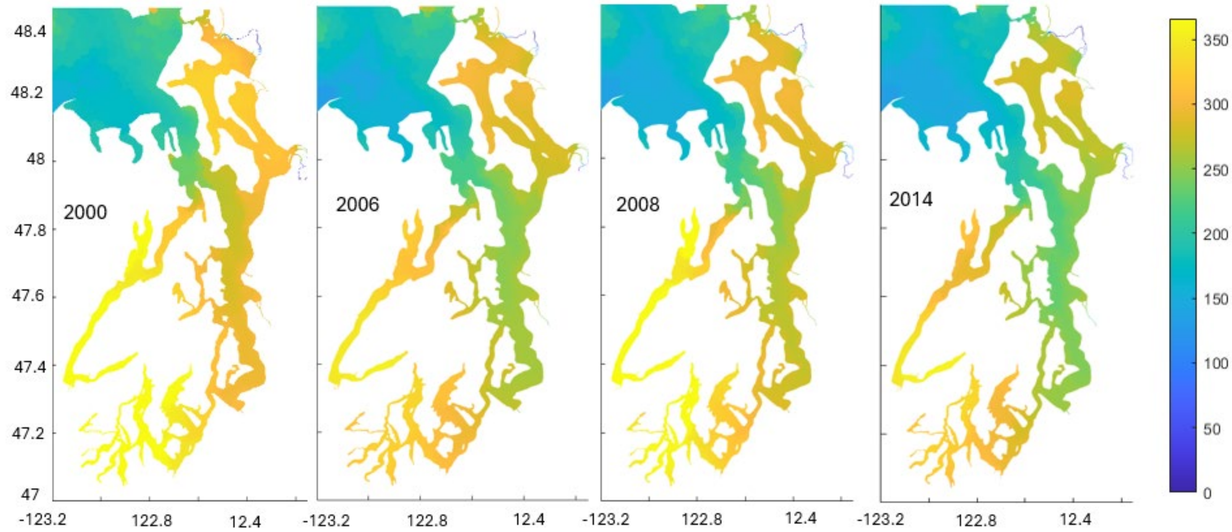

Figure M-4. Residence times for years 2000, 2006, 2008, and 2014 with initial dye in the PSM extent (Figure M-2) using SSM.

While the magnitudes of residence times are different due to the differences in how the tracer experiments were conducted, results show similar *relative* spatial patterns as were reported in Ahmed et al. (2019) for each year. Inter-annual variation reflected different trends than those computed via the Knudsen relationship (Figure M-1). The overall average winter flushing time for the PSM region in this study was found to be 316 days, 311 days, 292 days, and 279 days for years 2000, 2008, 2006, and 2014, respectively. In this analysis, the 2006 results do not reflect longer residence times in the central Main Basin or overall, and the year 2000 showed longer residence and flushing times relative to the other years analyzed.

Comparative analysis between basins

To assess flushing time magnitudes individually for different basins in greater Puget Sound, we introduced the tracer dye in each basin separately for each of the four years on January 1st and estimated e-folding times. The individual basins are shown in Figure M-5. The boundaries and names for these basins were kept consistent with those used by Premathilake and Khangaonkar (2022). The spatial boundaries for these basins are different than the definitions used elsewhere in this report and apply only to this analysis.

The difference in residence times for a given location within the basin reflects the distance of the location from the basin's open boundary and the hydrology of the specific year when the dye simulation was done. Each simulation was run from January 1st until December 31st. E-folding times were estimated from January 1st, when the initial dye was introduced. Overall, e-folding times across years reflect differences in hydrology and hydrodynamics between the years.

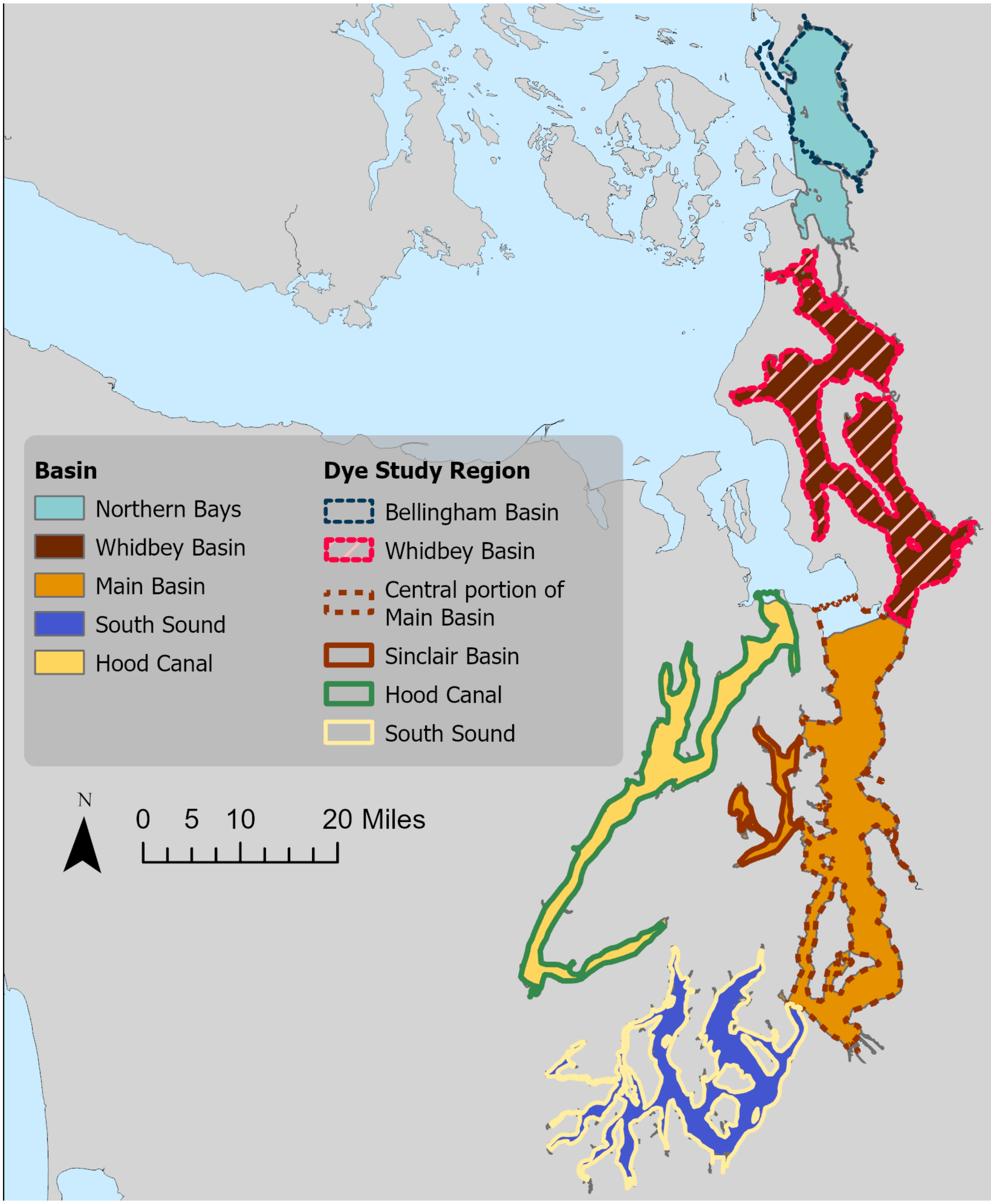

Figure M-5. Map showing the boundaries of the basins used for the virtual dye study.

Figure M-6 (left panel) shows the winter season residence times across Hood Canal for years 2000, 2006, 2008, and 2014. Residence time varies within Hood Canal, with the longest residence time in Lynch Cove and the smallest residence times near the open boundary of Hood Canal, as expected. The bar chart (Figure M-6, right panel) shows that the longest winter flushing time was for the year 2000, followed by 2006, 2014, and then 2008.

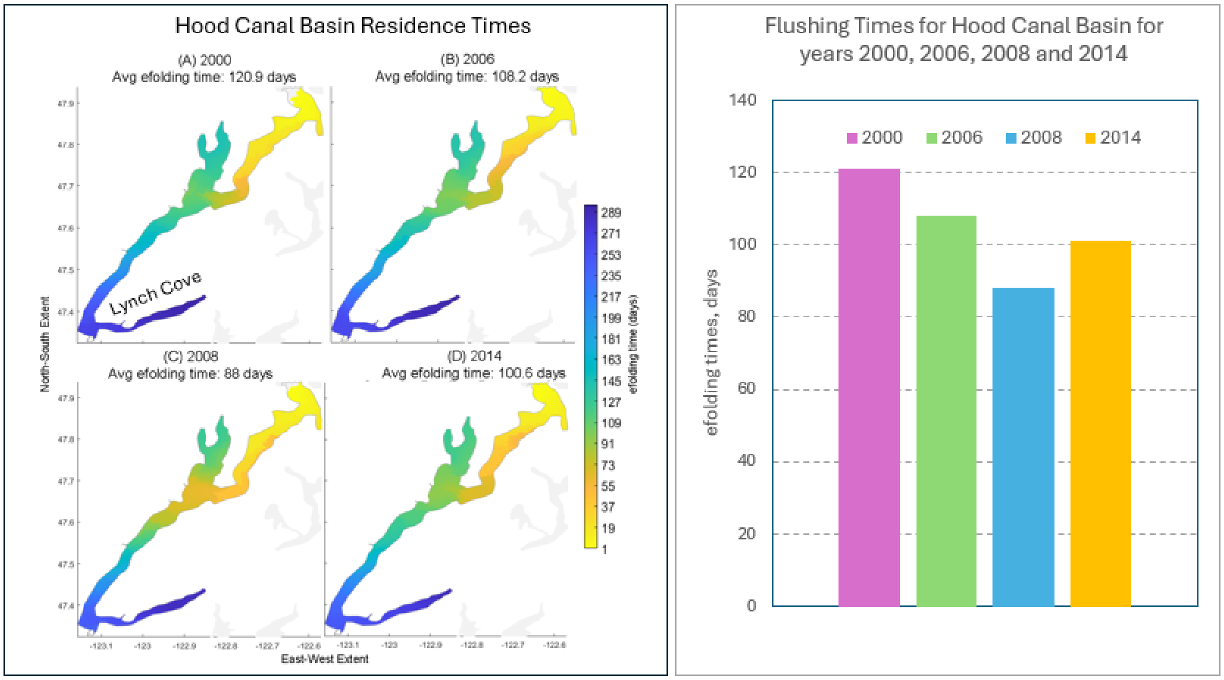

Figure M-6. Residence and flushing times in Hood Canal for years 2000, 2006, 2008, and 2014.

Figure M-7 (left panel) shows the winter season residence times across the central portion of the Main Basin for years 2000, 2006, 2008, and 2014. The bar chart shows that the longest winter flushing time was for the year 2000, followed by 2006, 2008, and then 2014. The planview map shows that the winter residence time varies within Central Basin, with the longest around Vashon Island and the shortest near the open boundary, as expected.

The relative residence times index (based on salt balance approach in summer months) for the central portion of the Main Basin in Figure M-1 for years 2006, 2008, and 2014 matches the relative winter flushing time trend for these years in Figure M-7. However, the relative reference time index (based on the salt balance approach in summertime) for the year 2000 was shown to be much lower than in other years in Figure M-1. However, the dye-based winter flushing time for 2000 was much higher than in other years, as shown in Figure M-7.

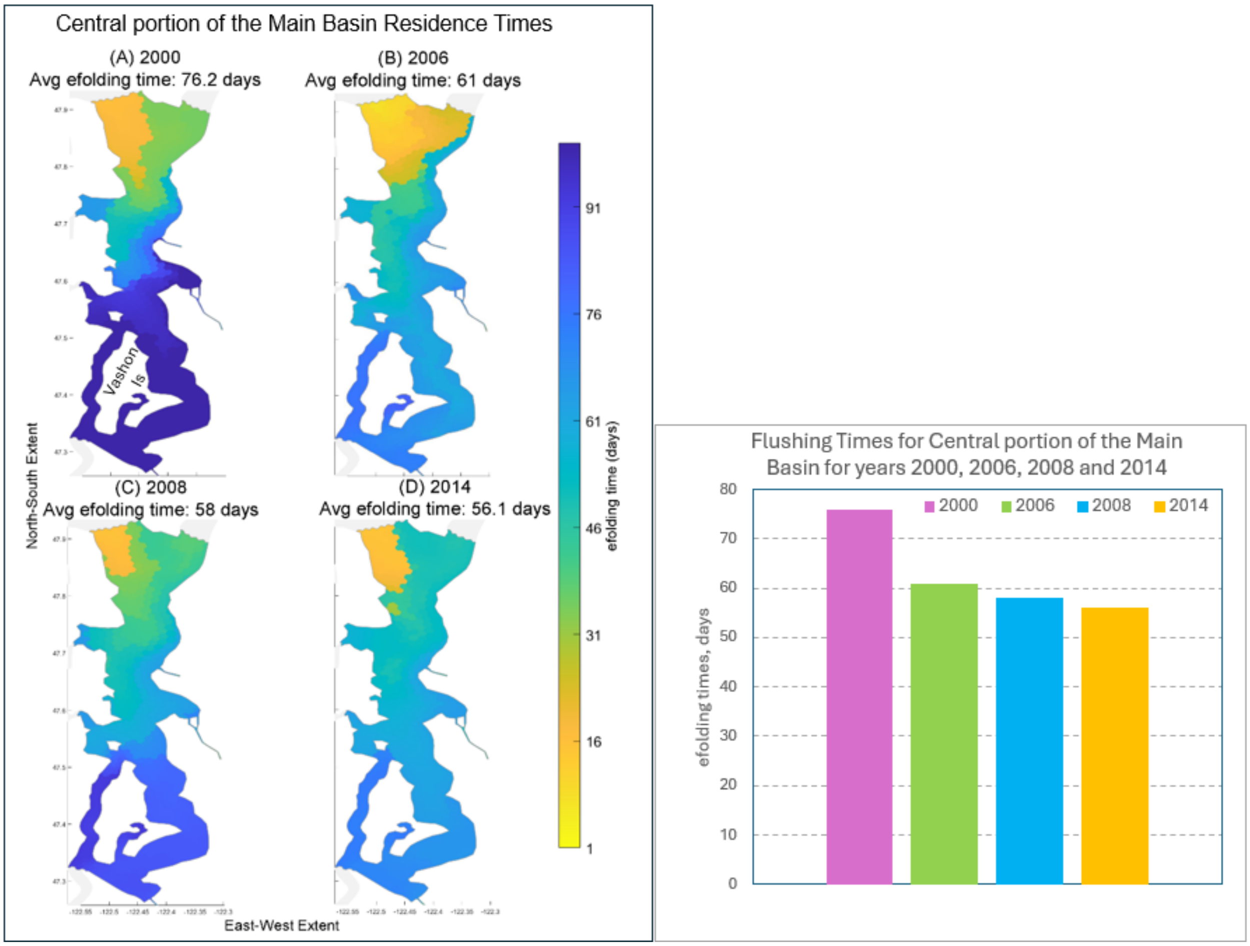

Figure M-7. Residence and flushing times in the central portion of the Main Bain for the years 2000, 2006, 2008, and 2014.

Figure M-8 (left panel) shows the winter residence times in South Sound. Cells with the longest residence times were located in headwaters of remote finger inlets away from the open boundary. The longest winter flushing time (Figure M-8, right panel) is in 2000, followed by 2014, 2008, and 2006.

Figure M-9 (left panel) shows the winter residence times in Whidbey Basin. Regions in Penn Cove, Port Susan, and Skagit Bay had the longest residence times. Note that in 2014, Oak Harbor RBC WWTP, located north of Penn Cove, had zero flows, which may have contributed to longer residence time in this area in 2014. Longest winter flushing time (Figure M-9, right panel) for Whidbey Basin was in year 2014, followed by 2000, 2008, and 2006.

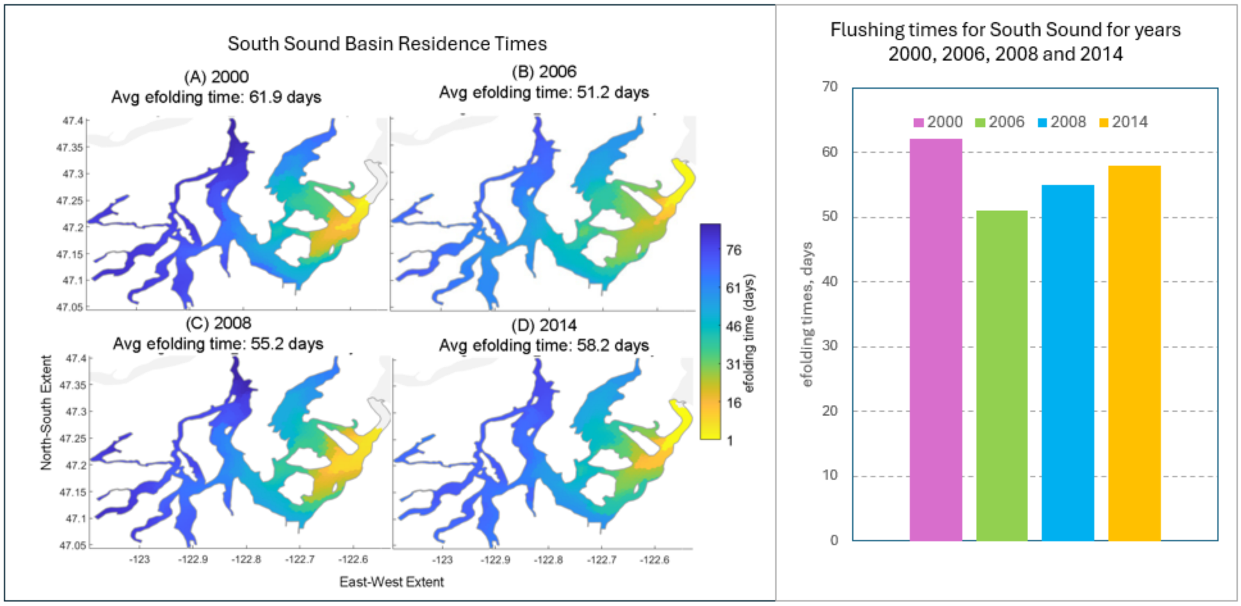

Figure M-8. Residence and flushing times in South Sound for the years 2000, 2006, 2008, and 2014.

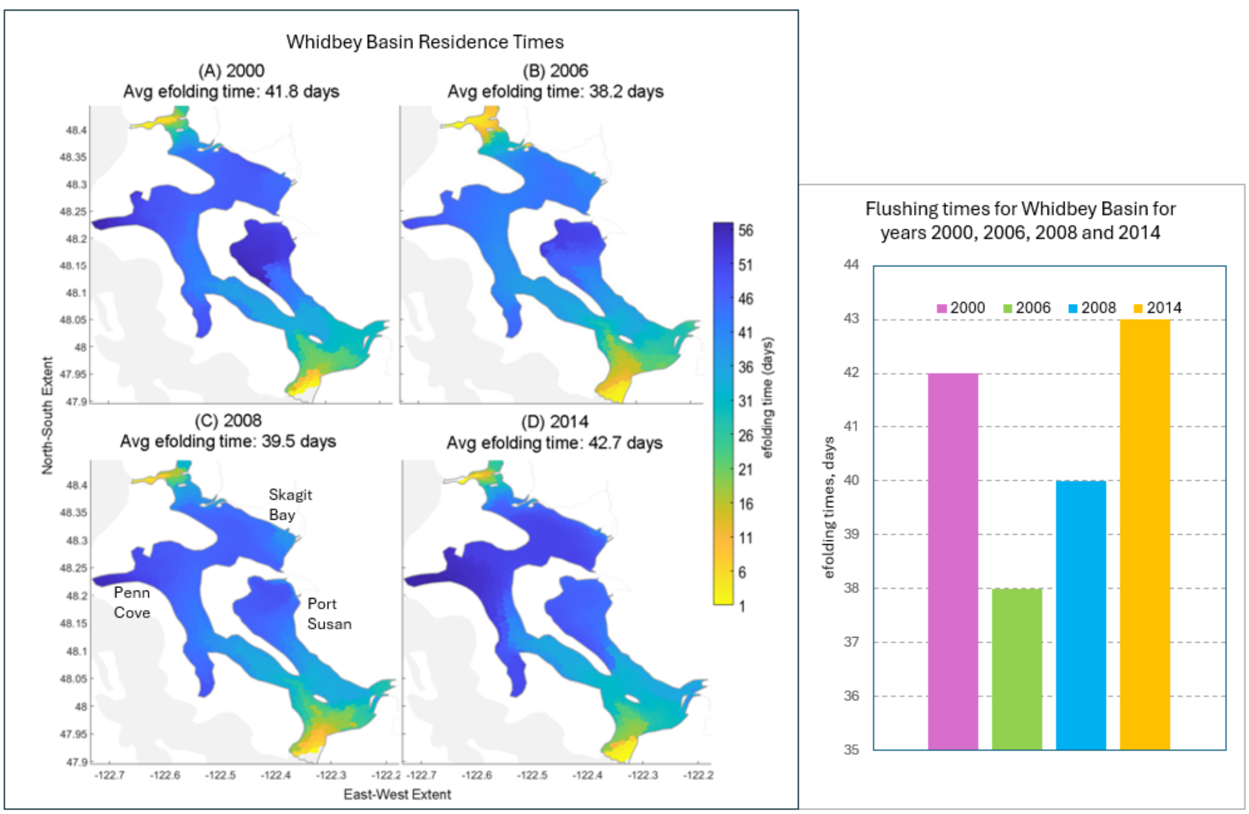

Figure M-9. Residence and flushing times in Whidbey Basin for years 2000, 2006, 2008, and 2014.

Bellingham Basin results are shown in Figure M-10. The left panel shows the winter residence times, and the right panel shows the winter flushing times. Again, the longest winter flushing times occurred in 2000, followed by 2014, with 2008 and 2006 having similar flushing times (bar chart in Figure M-10). The northern portion of the Bellingham Basin had relatively higher residence times compared with the rest of the basin.

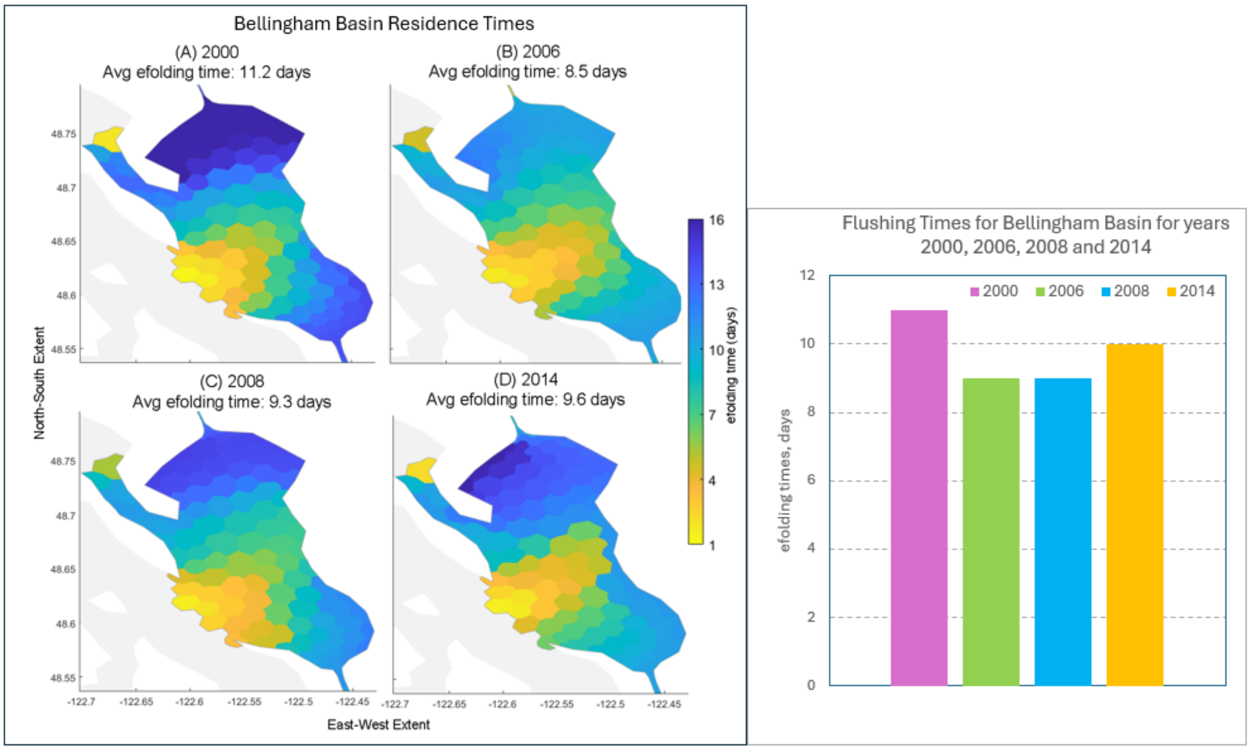

Figure M-10. Residence and flushing times in Bellingham Basins for the years 2000, 2006, 2008, and 2014.

For Sinclair Basin (comprising Sinclair Inlet, Dyes Inlet, and Liberty Bay), the winter residence (left panel) and flushing (right panel) times are shown in Figure M-11. The flushing time plot suggests that year 2014 had the longest winter flushing time, and 2008 the shortest, with 2000 and 2006 having similar but lower flushing times. It is interesting to note that the area most resistant to dissolved oxygen improvement in 2014 is at the tip of Sinclair Inlet.

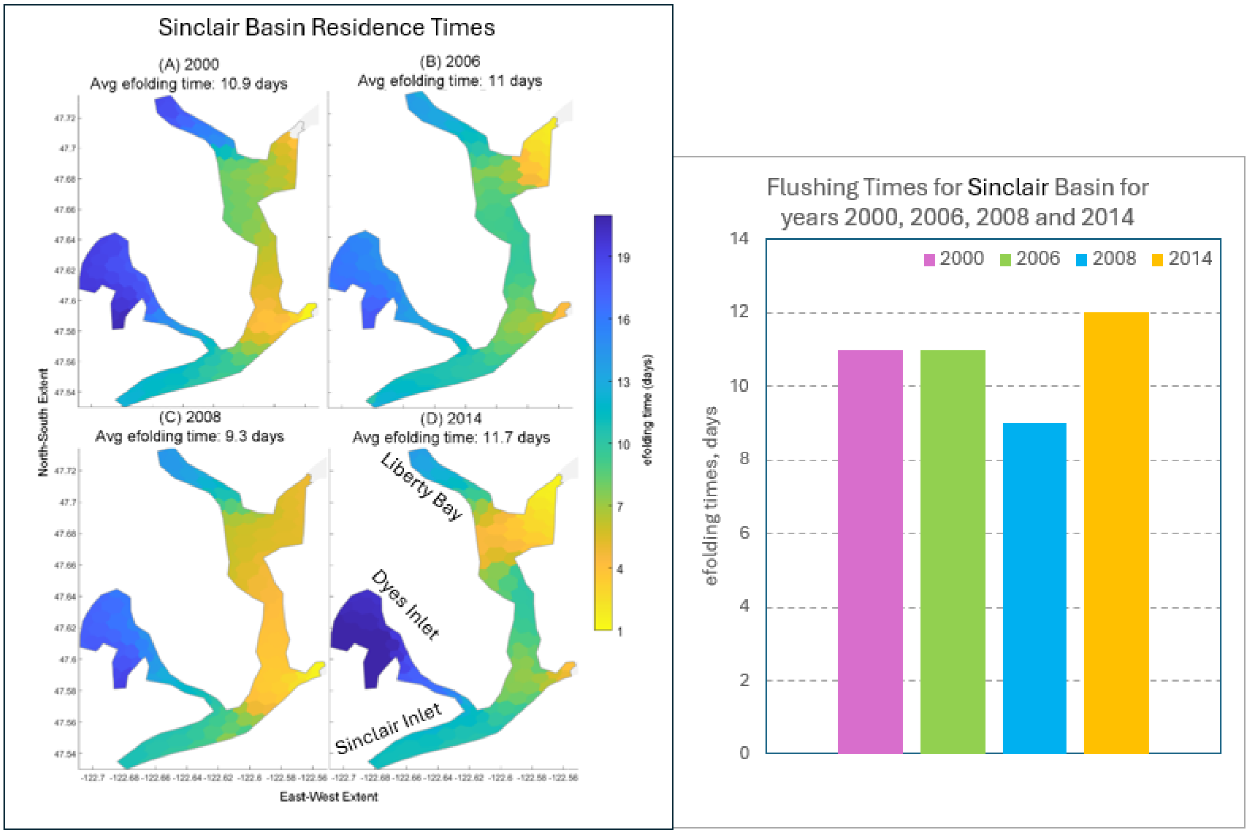

Figure M-11. Residence and flushing times in Sinclair Basin for the years 2000, 2006, 2008, and 2014.

Figure M-12 shows the average basin flushing times across all four years simulated (2000, 2006, 2008, and 2014). The averaging period is limited to the e-folding times measured from January 1st of each year. The plot shows Hood Canal having the longest flushing time, followed by the central portion of the Main Basin, South Sound, Whidbey Basin, Sinclair Basin, and Bellingham Basin. Note that for each of these basins, the open boundary for the dye study was different and was specific to the basin studied. Also note that the bar chart colors match the basin colors in Figure M-5.

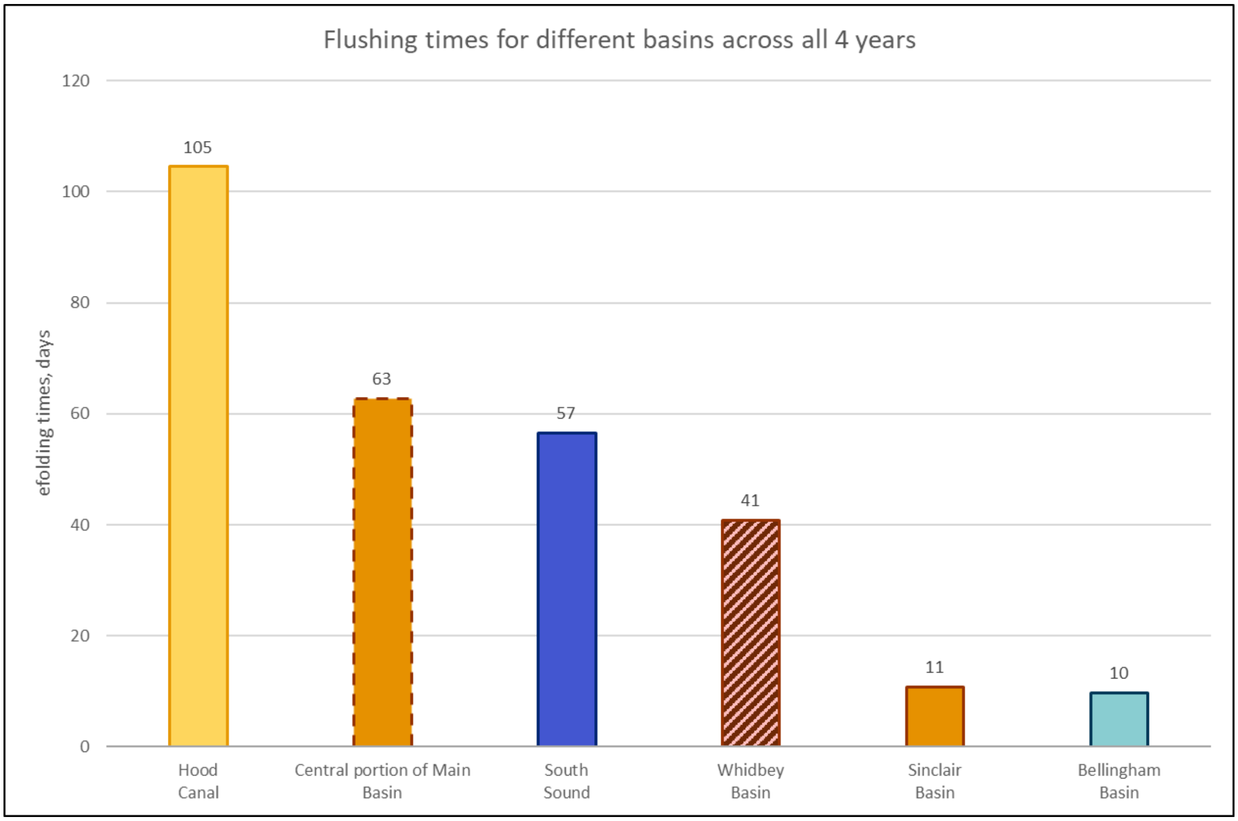

Figure M-12. Average basin flushing times across all four years (2000, 2006, 2008, and 2014).

The winter flushing times for the various basins are presented in Table M-1 with an average of the four years estimated in this study, along with the winter and summer flushing times estimated by Premathilake and Khangoankar (2022) for the year 2017. The flushing times calculated in this study should be compared with the winter flushing times estimated by Premathilake and Khangoankar (2022), as the dye was released, in the current study, on the first of January, similar to the dye release time in the winter season by Premathilake and Khangoankar (2022). Table M-1 includes flushing times (average of 2017, 2018, and 2019) estimated by McCready et al. (2021) for several basins using a 2-layer box model (McCready called his estimates residence times, but his calculations match the definition of flushing times used in this study). Table M-1 also includes flushing times estimated by Ahmed et al. (2017) using a three-dimensional GEMSS model of South and Central Puget Sound with initial virtual dye introduced on July 1, 2006.

Differences in flushing times can be attributed to several factors, including: coarser (present study) and finer (Premathilake and Khangoankar 2022) grids, the 2-layer box model (McCready et al. 2021), and inter-annual differences in hydrology and whether the dye study was conducted during high winter or low summer flows. However, despite all these differences, it is clear that Hood Canal has the longest flushing times relative to other basins.

Table M-1. Comparison of flushing times in this study with those of Premathilake and Khangoankar (2022), McCready et al. (2021), and Ahmed et al. (2017).

Basin	This study[1]	Premathilake and Khangoankar[2]	McCready et al.[3]	Ahmed et al.
Hood Canal	105	80–138	143	—
South Sound	57	40–40	125	65
Whidbey Basin	41	24–32	60	—

[1] Average of 2000, 2006, 2008, and 2014.

[2] 2017 (winter – summer).

[3] Average of 2017, 2018, and 2019.

Comparative analysis of residence and flushing times in inlets and heads of embayment

We also analyzed e-folding times in specific inlets and heads of embayment in Puget Sound, which represent smaller areas within some of the basins discussed earlier: Lynch Cove (in Hood Canal), Case and Carr Inlets (in South Sound), and Sinclair Inlet (in Main Basin). The boundaries and names for these areas were kept consistent with those used by Premathilake and Khangaonkar (2022) and are shown in Figure M-13.

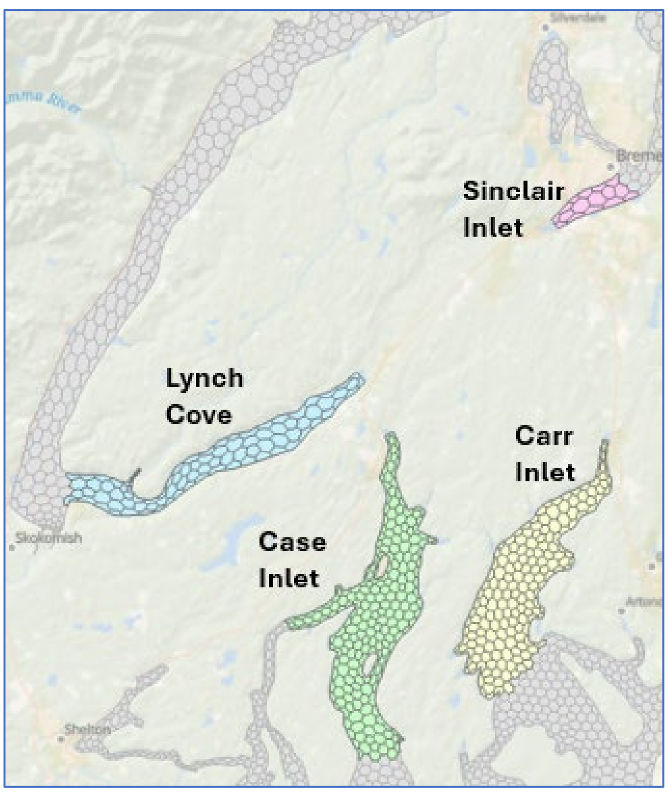

Figure M-13. Boundaries of heads of embayment used for virtual dye study.

To assess residence and flushing time magnitudes individually for each inlet, we introduced a virtual dye tracer within the boundaries of each inlet and separately for each of the four years on January 1st. The difference in within-inlet residence times reflects the distance of the location from the inlet's defined open boundary, at each inlet's mouth, and the hydrology of that year. Flushing times across years reflect the differences in hydrology and hydrodynamics of the years.

Figures M-14 and M-15 show the winter residence (left panel) and winter flushing (right panel) times in Case and Carr inlets, respectively. Again, the highest winter residence times within the inlet were limited to remote cells away from the open boundary, as expected. Winter flushing times in Case Inlet (Figure M-14) were longest and the same for 2000 and 2014, followed by 2008 and 2006. Winter Flushing times in Carr Inlet (Figure M-15) were longest for 2008, followed by 2000 and 2014 (with similar winter flushing times) and then 2006 (with the lowest winter flushing time).

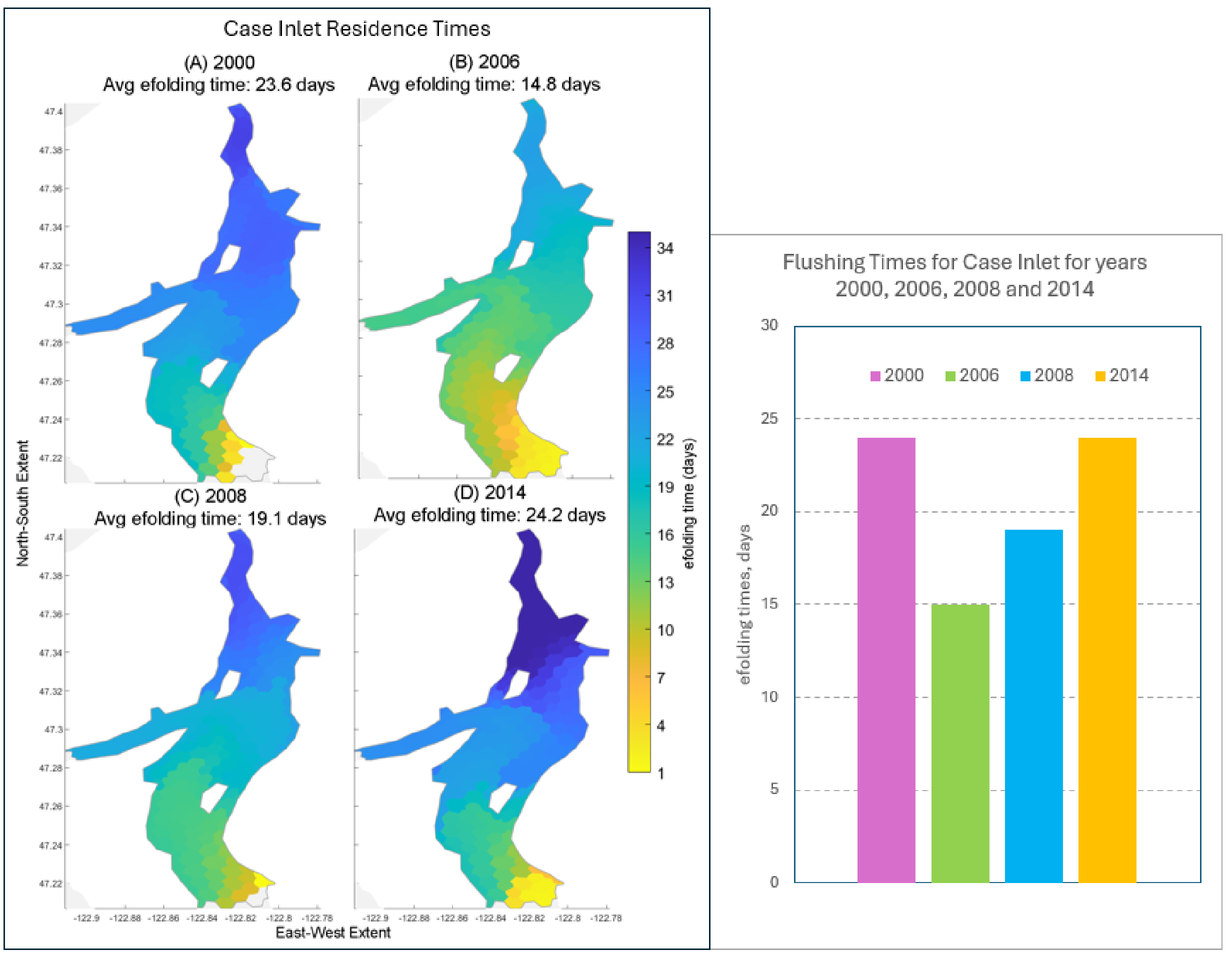

Figure M-14. Residence and flushing times in Case Inlet for the years 2000, 2006, 2008, and 2014.

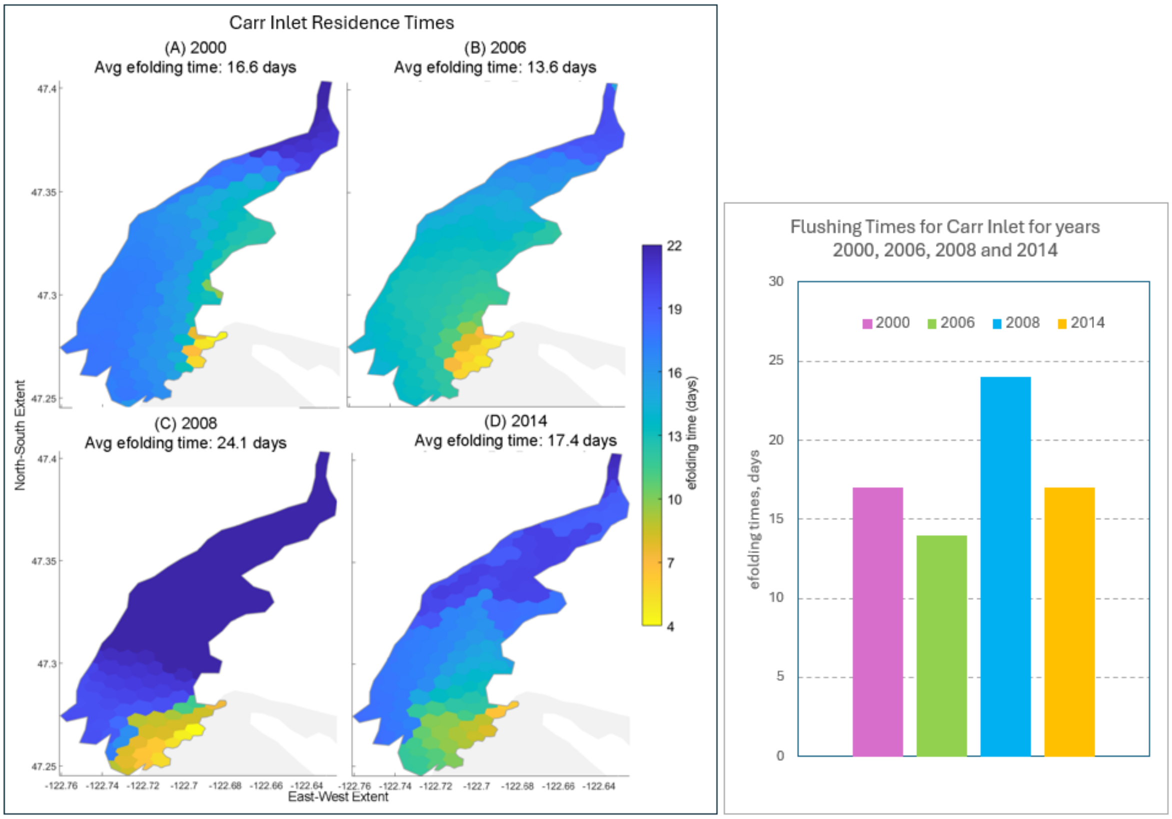

Figure M-15. Residence and flushing times in Carr Inlet for the years 2000, 2006, 2008, and 2014.

Figure M-16 shows the winter residence (left panel) and flushing (right panel) times for Lynch Cove. The longest winter flushing time in Lynch Cove was in 2014, followed by 2000,2006, and 2008.

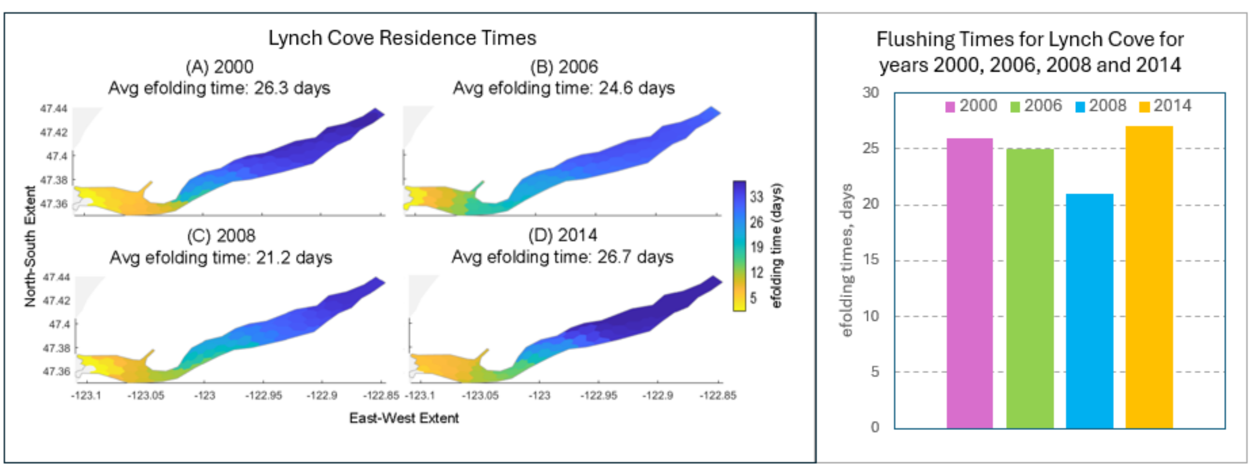

Figure M-16. Residence and flushing times in Lynch Cove for the years 2000, 2006, 2008, and 2014.

Figure M-17 shows the winter residence (left panel) and flushing (right panel) times for Sinclair Inlet. The longest winter flushing time in Sinclair Inlet was in 2014, followed by 2000 and 2008 (which had the same flushing times), with the lowest flushing time for 2006.

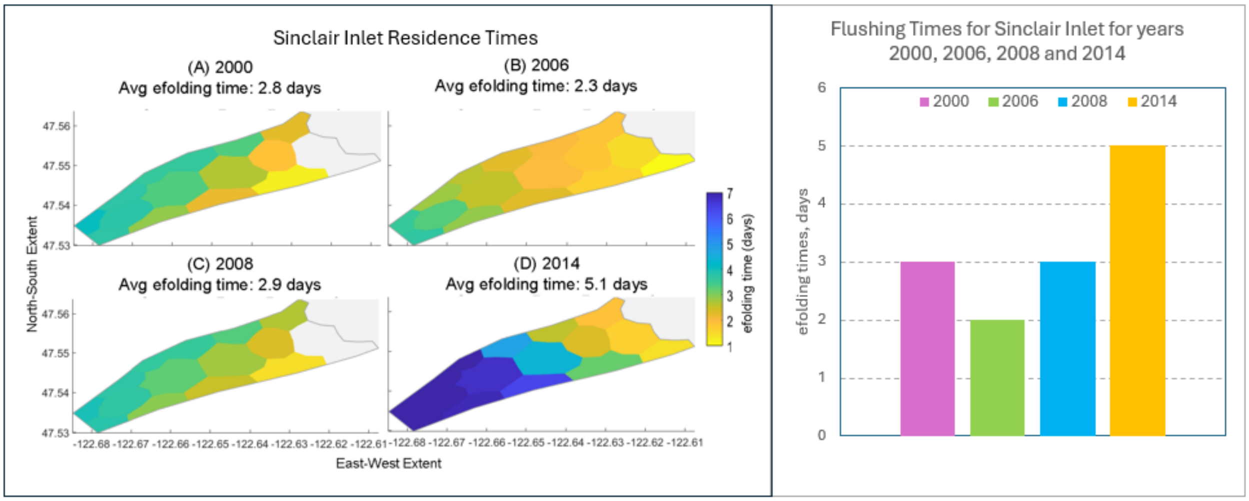

Figure M-17. Residence and flushing times in Sinclair Inlet for the years 2000, 2006, 2008, and 2014.

Figure M-18 shows the average flushing times for inlets and head of embayment across all four years simulated (2000, 2006, 2008, and 2014). The averaging period is limited to the e-folding times measured from January 1st of each year. The plot shows that Lynch Cove has the longest average flushing time, followed by Case Inlet, Carr Inlet, and finally Sinclair Inlet.

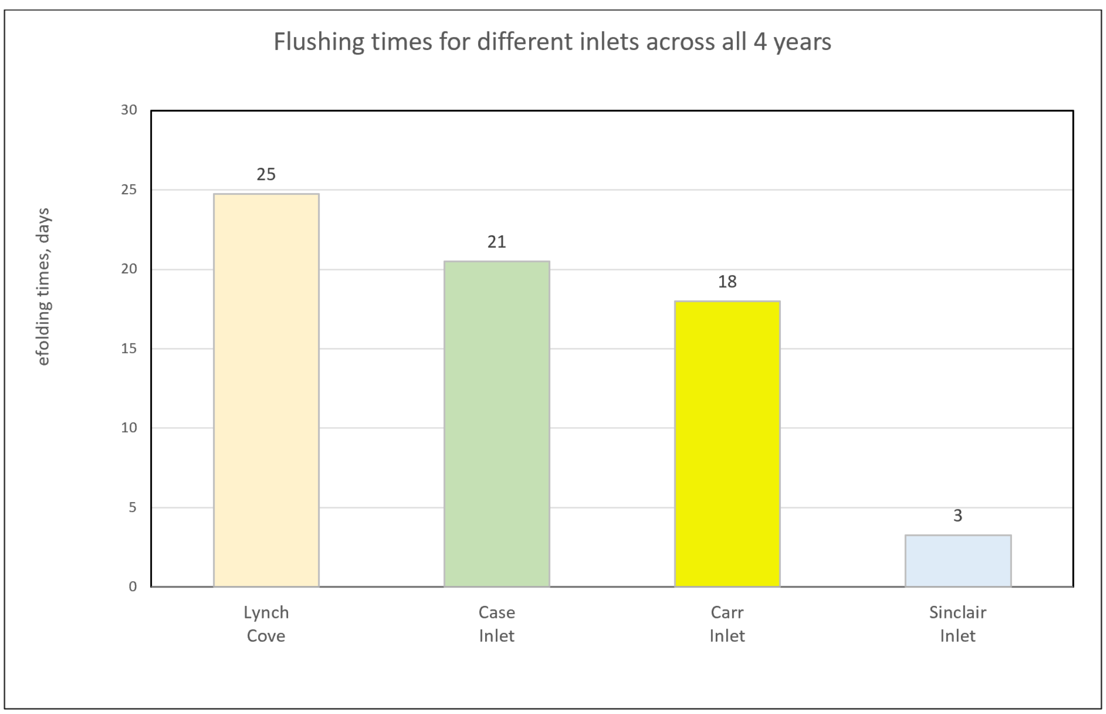

Figure M-18. Average inlet flushing times across all four years (2000, 2006, 2008, and 2014).

Table M-2 shows a comparison of winter flushing times estimated in this study (average of four years, 2000, 2006, 2008, and 2014) for the various inlets and heads of embayments and those estimated by Premathilake and Khangoankar (2022). Lynch Cove was found to have the longest winter flushing time in both studies compared to those of the other inlets studied.

Table M-2. Comparison of winter flushing times for inlets and heads of embayment.

Basin	This study[1]	Premathilake and Khangoankar (2022)[2]
Lynch Cove	25	18
Case Inlet	21	18
Carr Inlet	18	12
Sinclair Inlet	3	6

[1] Average of 2000, 2006, 2008, and 2014 winter.

[2] 2017 winter.

Summary

In contrast to Ahmed et al. (2019), in this study, we produce winter residence and flushing time estimates that are influenced by the re-entry of virtual tracer dyes. Reflux of waters within the estuary plays an important role in e-folding time estimates.

Key results from this analysis are:

1. Differences in approaches, boundaries, and time scale averages lead to differences in e-folding time estimates (this study, Premathilake and Khangaonkar 2022; MacCready et al. 2021; Ahmed et al. 2019). Nonetheless, the relative variation among flushing times for basins is well established from longest to shortest in this order: Hood Canal, South Sound, Whidbey Basin. For inlets and heads of embayment studied, the longest to shortest flushing times are in the following order: Lynch Cove, Case Inlet, Carr Inlet, and Sinclair Inlet. Figure M-19 summarizes the flushing times across all basins and inlets. Lynch Cove at the headwaters of Hood Canal comprises of almost 25% of the flushing time for Hood Canal. Sinclair Inlet comprises almost 33% of flushing time for Sinclair Basin. In South Sound Basin, Case and Carr inlets together represent almost 68% of the total flushing time for South Sound.

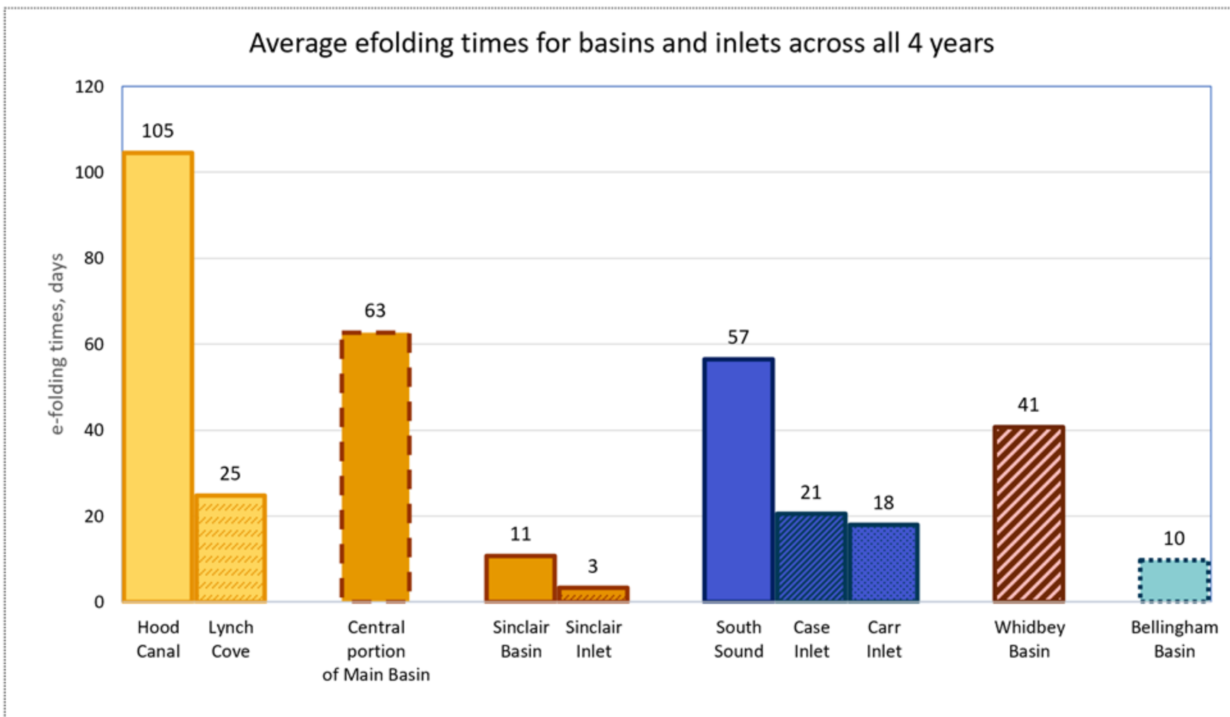

Figure M-19. Summary of flushing times across all basins and inlets.

2. Among the four years studied, the overall winter flushing times for the Greater Puget Sound (PSM model domain) extent of the Salish Sea in order of longest to shortest are: 2000, 2008, 2006, and 2014. However, winter flushing times vary by individual basins and year within the Greater Puget Sound.
3. Salt-balance (Burchard et al. 2018) based residence time provides useful information, but in the case of residence times for the year 2000 (Albertson et al. 2016), a much shorter residence time at a location in Main Basin was estimated relative to other years. However, computations from virtual dye-based residence times using SSM show that the year 2000 in the winter had the longest residence time for the central portion of the Main Basin compared to other modeled years.

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