# Appendix 9.F. Surface Salinity Partial-Duration Frequency Analyses

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# Introduction

Submerged aquatic vegetation (SAV) is present throughout the St. Johns River (SJR) and is an important functional component of this aquatic ecosystem. Within the Lower St. Johns River (LSJR), SAV occurs both within lakes and in broad littoral shelves within the main stem of the river (Sagan 2009). There is concern that SAV will decrease in spatial extent in the LSJR due to an increase in the magnitude, frequency, and/or duration of salinity events resulting from proposed surface water withdrawals from the SJR. In order to determine whether this is likely, salinities resulting from simulations of several potential water management alternatives (for the period 1996-2005, (Chapter 6. River Hydrodynamics Results) were compared at several SAV monitoring stations with partial-duration frequency analysis.

# Methods

## Site Selection

Established St. Johns River Water Management District (SJRWMD) SAV monitoring stations occur along the LSJR (Figure 1, Appendix 9.A). The stations with the largest fluctuations of salinity in conjunction with the historic presence of *Vallisneria americana* (hereby referred to as Vallisneria) were selected as representative of river reaches exhibiting SAV stress, extreme stress, and possible mortality, thereby defining the salinity tolerance edge of Vallisneria. The JAXSJR40 station (Figure 1) is the SJRWMD water monitoring station located mid-channel between the Fuller Warren Bridge and the Buckman Bridge. This is the most downstream of the SAV monitoring stations and is no longer regularly monitored because there is currently no SAV present. SAV (mainly Vallisneria) was documented in the littoral zone near that station from 1996-1998 (*Personal communication*, Dean Dobberfuhl, SJRWMD Technical Program Manager Upper SJR Basin). SAV has since been extirpated in this area due to an increase in the magnitude, duration, and/or frequency of high salinity events, thought to be the causative factor for SAV decline and subsequent extirpation.

Since the JAXSJR40 station is near a location that can support SAV given favorable salinity conditions but does not support SAV given unfavorable conditions, the modeled maximum surface salinity data for JAXSJR40 was used to define the threshold salinity tolerance regime for Vallisneria-dominated SAV in the LSJR. Maintenance of SAV at a site would depend on not exceeding this threshold. This salinity threshold was used to compare to the modeled salinity at the next upstream SAV monitoring station (Figure 1), Bolles School (SAVBOLSI). In a similar manner, the salinities at Buckman Bridge (SAVBUCBI) were compared to the salinity regime at Bolles School. Acryonyms and location descriptions of these SAV monitoring stations are summarized in Table 1.

## Model Scenario Selection

Modeled daily maximum surface salinity at the JAXSJR40, Bolles School (SAVBOLSI), and Buckman Bridge (SAVBUCBI) SAV monitoring stations were downloaded from the SJRWMD Time-Series Web Intranet data interface (SJRWMD 2010). Eight modeled scenarios were downloaded but only three were used in analyses at each SAV monitoring station: the 1995 land use with no extra withdrawals, no upper basin projects and no sea level rise (“**Base1995NN”**); 1995 land use with the full modeled SJR withdrawal with the full modeled Ocklawaha River withdrawal, no upper basin projects and no sea level rise (“**FwOR1995NN”**); and the 2030 land use with the full modeled SJR withdrawal with the full modeled Ocklawaha River withdrawal, inclusion of upper basin projects and sea level rise (“**FwOR2030PS”**) (Table 2).

The “**Base1995NN**” modeling scenario represents the baseline hydrologic conditions. The “**FwOR1995NN**” modeling scenario represents conditions that will not occur in the future. The “**FwOR2030PS**” modeling scenario represents the most likely future hydrologic conditions. These three modeled water management scenarios were deemed representative of the range of salinity conditions expected for all other modeled water management scenarios (Chapter 6. River Hydrodynamics Results, Table 3-2).

## Frequency Analyses

The hydrologic and salinity simulations performed for the SJR Water Supply Impact Study (WSIS) produced time series of daily data (e.g., surface salinities) for various locations along the SJR. Of interest are the frequency of occurrence of specific events, such as surface salinities continuously exceeded for certain durations. The SWIS simulations were performed for a number of water management scenarios (Table 2) at the three stations of interest. This section briefly describes the concepts of frequency analysis and presents the methods used to evaluate salinity events from the daily time series data.

Frequency analysis estimates how often, on average, a given event will occur. If annual series hydrologic data were used to generate the statistics, frequency analysis estimates the probability of a given hydrologic event happening in any given year.

A simple example illustrates some of the concepts basic to frequency analysis. A frequently used statistic with respect to water level is the yearly peak stage of a water body. If a gauge has been monitored for 10 years, then there will be 10 yearly peaks $S_1, S_2, \cdots, S_{10}$. Once sorted and ranked, these events can be written as $\hat{S}_1, \hat{S}_2, \cdots, \hat{S}_{10}$, with $\hat{S}_1$ being the highest peak. Based on this limited sample, the estimated probability of the yearly peak being greater than or equal to $\hat{S}_1$ would be

$$P(S \geq \hat{S}_1) = \frac{1}{n} = \frac{1}{10} = 0.1\text{;} \qquad \text{Equation (1)}$$

the probability of the 1-day peak stage in any year being greater than $\hat{S}_2$

$$P(S \geq \hat{S}_2) = \frac{2}{10} = 0.2\text{;} \qquad \text{Equation (2)}$$

and so on. The probability of the stage equaling or exceeding $\hat{S}_{10}$ would be

$$P(S \geq \hat{S}_{10}) = \frac{10}{10} = 1.0\text{.} \qquad \text{Equation (3)}$$

Because this system of analysis precludes any peak stage from being lower than $\hat{S}_{10}$, the usual convention is to divide the stage continuum into 11 parts: nine between each of the 10 peaks, one above the highest peak, and one below the lowest peak ($n - 1 + 2 = n + 1 = 11$). This suggests what is known as the Weibull plotting position formula:

$$P(S \geq \hat{S}_m) = \frac{m}{n+1} \qquad \text{Equation (4)}$$

where,

$P(S \geq \hat{S}_m) =$ probability of $S$ equaling or exceeding $\hat{S}_m$

$m =$ rank of the event

Thus, in the example, the probability of the peak in any year equaling or exceeding $\hat{S}_1$ would be

$$P(S \geq \hat{S}_1) = \frac{1}{n+1} = \frac{1}{11} = 0.0909\,; \qquad \text{Equation (5)}$$

the probability of the 1-day peak stage in any year being greater than $\hat{S}_{10}$

$$P(S \geq \hat{S}_{10}) = \frac{10}{11} = 0.9091\,; \qquad \text{Equation (6)}$$

and so on. The probability the stage in any year is smaller than $\hat{S}_{10}$ would be

$$P(S < \hat{S}_{10}) = 1 - P(S \geq \hat{S}_{10}) = 1 - \frac{10}{11} = 1 - 0.9091 = 0.0909 \qquad \text{Equation (7)}$$

The return period (in years) of an event, $T$, is defined as

$$T = \frac{1}{P} \qquad \text{Equation (8)}$$

so the return period for $\hat{S}_1$ would be

$$T(\hat{S}_1) = \frac{1}{P(S \geq \hat{S}_1)} = \frac{1}{\frac{1}{11}} = 11 \qquad \text{Equation (9)}$$

Said another way, $\hat{S}_1$ would be expected to be equaled or exceeded, on average, once every 11 years.

As the size of the sample increases, the probability of $\hat{S}_1$ being equaled or exceeded decreases. Thus, with $n = 20$,

$$P(S \geq \hat{S}_1) = \frac{1}{n+1} = \frac{1}{21} = 0.048$$ Equation (10)

and

$$T(\hat{S}_1) = \frac{1}{P(S \geq \hat{S}_1)} = 21$$ Equation (11)

The salinity characteristics of a water body can be summarized using the Weibull plotting position formula and a frequency plot.

### Evaluation of salinity events: Partial-duration frequency analysis

Figure 2 shows the modeled daily maximum salinities for the SJR at JAXSJR40 in Jacksonville for the period 1996 – 2005 (Scenario:Base1995NN). From this figure, one may observe that a given salinity concentration was continuously exceeded (or not exceeded) for a number of days one or more times in a given year. Such occurrences are defined as "**events**" for the present analysis.

The standard hydrologic frequency analysis is one based on the annual series of events. This presumes that there is one maximum (or minimum) event per year. However, often there might be more than one event that exceeds a given threshold in any given year. This is certainly the case with salinity where there may be a number of salinity peaks of consequence in a given year. This eventuality is provided for in partial-duration series analysis. The assigning of probability of occurrence of events in partial-duration series analysis (USGS 1982) is much like with annual-series analysis, except that all events above a given threshold are ranked and sorted. However, the divisor in the Weibull plotting-position formula remains the number of years of record plus one (See Equation 10).

For the partial-duration frequency analysis of salinity events, various threshold salinity values (TSV) were selected (1.0, 2.0, 3.0, 5.0, 10.0, 15.0. 20.0, 25.0 practical salinity units [psu]; Table 3). The data were analyzed to determine the number of days and the number of times the TSV was exceeded during the period of model simulation (1996 – 2005). For example, a TSV of 15-psu was exceeded 29 times and the TSV of 20-psu was exceeded 12 times for different durations during the simulation period of 1996 – 2005 for the FwOR2030PS alternative (Table 3). The analysis also determined the duration of each event and the time elapsed between the consecutive events. The partial-duration events are arranged in order of magnitude (i.e., ranked) and the probabilities for each event are calculated by Equation 4. These data are plotted on a Weibull probability graph (Figure 3).

## Results and Discussion

Although the salinity regime at a location is certainly not the only factor influencing the presence and abundance of SAV, it is one of the principal factors in the LSJR. JAXSJR40 is a location where SAV previously occurred under favorable conditions, but has since been extirpated. Therefore, the salinity regime at that location may provide a threshold beyond which it would be undesirable to move. A regime can be thought of as a combination of salinity concentrations and the associated durations and return intervals of those concentrations. Salinity affects SAV on any one or more of these three aspects (Appendix 9.A).

The best way to compare the salinity from one location to another is to construct a regime by fitting levels of salinity with a series of best-fit lines. Figure 3 shows the salinity regime at JAXSJR40. Best-fit lines were drawn through the partial-duration series of events from the Base1995NN scenario. This scenario represents something of an “existing conditions” scenario against which other alternatives can be compared. The changes in salinity at JAXSJR40 caused by different water management alternatives can be examined by plotting the corresponding salinity partial-duration series events for two additional model simulations, “FwOR1995NN” and “FwOR2030PS” (Figure 4). While the exposure durations in mid-range salinities (≤10-psu) for these two model scenarios are expected to show very small increases in salinity exposure (i.e., 1 - 5 days) for annual exceedence probabilities greater than 60%, larger increases in salinity exposure (i.e., 30 - 40 days) are expected to occur less frequently (i.e., at exceedence probabilities less than 60%). The exposure durations of high-range salinities (≥ 15-psu) are predicted to increase only slightly (i.e., 0 - 5 days, Figure 4) for both scenarios. The general trend in the “FwOR2030PS” (future case) scenario is to cause smaller increases in salinity exposure across the salinity regime than the “FwOR1995NN” scenario (Figure 4).

Generally speaking, SAV becomes more abundant as one goes upstream from JAXSJR40. Salinities at the next upstream SAV station from JAXSJR40, Bolles School (SAVBOLSI), were compared with the salinity regime at JAXSJR40 to evaluate whether certain water management scenarios would cause the salinity regime at SAVBOLSI to shift beyond the JAXSJR40 threshold salinity regime (Figure 5). Salinities for the three alternatives at SAVBOLSI were plotted and compared to the “Base1995NN” salinity regime at JAXSJR40 (Figure 5). For the “FwOR1995NN” SAVBOLSI alternative, salinities at both 10- and 15-psu are nearing the corresponding level at JAXSJR40, but do not cross the corresponding salinity threshold. If a water management alternative similar to the Bolles School “FwOR1995NN” were to be instituted, this might be of some concern with respect to SAV.

Comparisons of the three modeled water management scenarios at Bolles School indicated that while the daily exposure in mid-range salinities (≤ 10-psu) are expected to show small increases (i.e., 5 - 15 days) for annual exceedence probabilities greater than 50%, larger increases in exposure (i.e., 15 - 45 days) are expected to occur less frequently (i.e., at exceedence probabilities less than 50%). The daily exposure of high-range salinities (≥ 15-psu) are predicted to increase only slightly (i.e., 0 - 10 days, Figure 5). The general trend in the JAXSJR40 “FwOR2030PS” (future case) scenario was to cause smaller increases in salinity exposure across the salinity regime than the JAXSJR40 “FwOR1995NN” scenario (Figure 5).

The “Base1995NN” salinity regime at Bolles School (SAVBOLSI) was also delineated (Figure 6) in order to compare it to salinities at the next upstream station, Buckman Bridge (SAVBUCBI). It is interesting to note that the distribution of 10-psu events at SAVBUCBI (Figure7) for all three alternatives seem to be similar to that at SAVBOLSI. It may be worth investigating if 10-psu or thereabouts (in combination with 20- to 40-day event durations) is determined to be of special significance to SAV on this particular stretch of the river.

Comparisons of the three modeled water management scenarios at Buckman Bridge indicated that the daily exposure in mid-range salinities (≤ 10-psu) are expected to show small increases (i.e., 5 - 15 days) for annual exceedence probabilities greater than 50%, larger increases in exposure (i.e., 5 - 35 days) are expected to occur less frequently (i.e., at exceedence probabilities less than 50%). The daily exposure of high-range salinities (≥ 15-psu) are predicted to increase only slightly (i.e., ~2 days, Figure 7). As observed at the other two monitoring stations, the general trend in the JAXSJR40 "FwOR2030PS" (future case) scenario was to cause smaller increases in salinity exposure across the salinity regime than the "FwOR1995NN" scenario (Figure 7).

## Conclusions

The partial-duration frequency analysis of the LSJRB salinity regime indicated that the daily exposure in mid- (≤ 10-psu) and high-range (≥ 15-psu) salinities are expected to show increases in days of exposure as a result of upstream surface water withdrawals from the SJR. Mid-range salinities (≤ 10-psu) showed small increases (i.e., 5 - 15 days) for annual exceedence probabilities generally greater than 50%, and larger increases in exposure (i.e., 5 - 35 days) were predicted to occur less frequently (i.e., at exceedence probabilities less than 50%). The daily exposure of high-range salinities (≥ 15-psu) are predicted to increase only slightly (i.e., ~2 days).

The results clearly show mid-range salinities as the most sensitive to decreases in river discharges resulting from surface water withdrawals. However, the increase in the duration of exposure to mid-range salinities is not expected to impact SAV because the greatest increases (i.e., > 20 days) occurred less frequently (i.e., recurrence intervals > 5 years) and provide adequate time for SAV recovery. High-range salinities showed only slight increases in durations of exposure, because ocean intrusions into the LSJR dominate high-range salinities. Decreased SJR discharge in the range represented by the water management alternatives has very little influence on these storm-driven events.

Generally speaking, salinity changes for the "FwOR2030PS" (future case) scenario are less severe than those for the "FwOR1995NN" scenario. This difference/pattern of change is an indication that increased freshwater runoff in the 2030 alternative offsets effects from both withdrawals and sea level rise.

## References

Sagan, J. J. 2009. Summary of submerged aquatic vegetation (SAV) status within the lower St. Johns River: 1996–2007. Final report to the St. Johns Water Management District contract number SJ45514. 167 pp.

[USGS] U.S. Geological Survey. 1982. *Guidelines for Determining Flood Flow Frequency.* Bulletin 17B. Reston, Va.: Interagency Advisory Committee on Water Data.

[SJRWMD ] St. Johns River Water Management District. 2010. Draft Modeled Data for Water Supply Impact Study. Downloaded December 10, 2010. SRJWMD Intranet web address: http://tsweb.sjrwmd.com/wiskiwebpro/main.php?sid=khd5r5thoskvfp9ep1pphgfpo7.

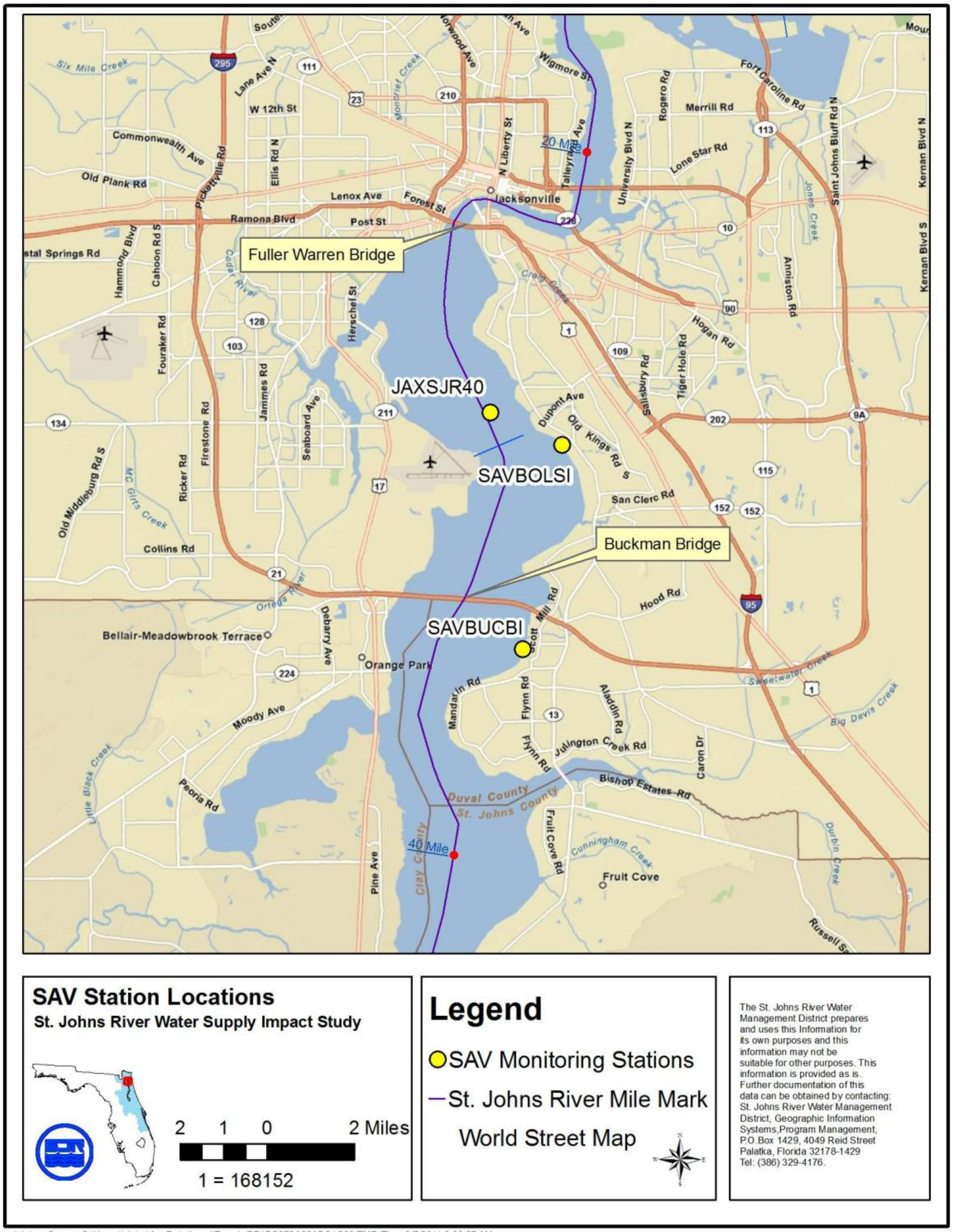


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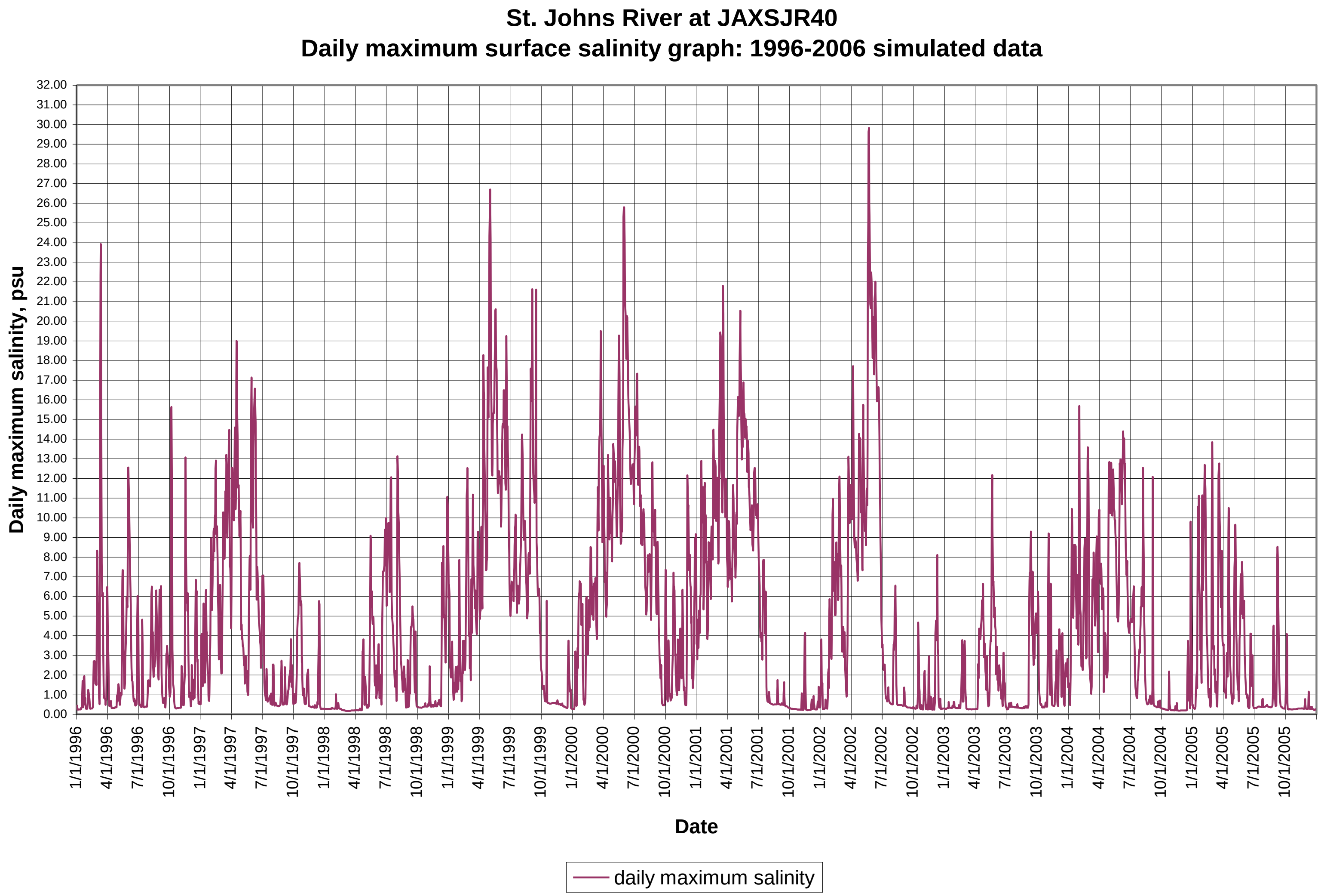
Figure 1. Location of three SAV monitoring stations [JAXSJR40, Bolles School (SAVBOLSI), and Buckman Bridge (SAVBUCBI)] considered for daily maximum surface salinity partial-duration frequency analysis

Figure 2. St. Johns River at SR40 in Jacksonville: Modeled daily surface salinity maximum (psu, practical salinity units) for 1996 - 2005



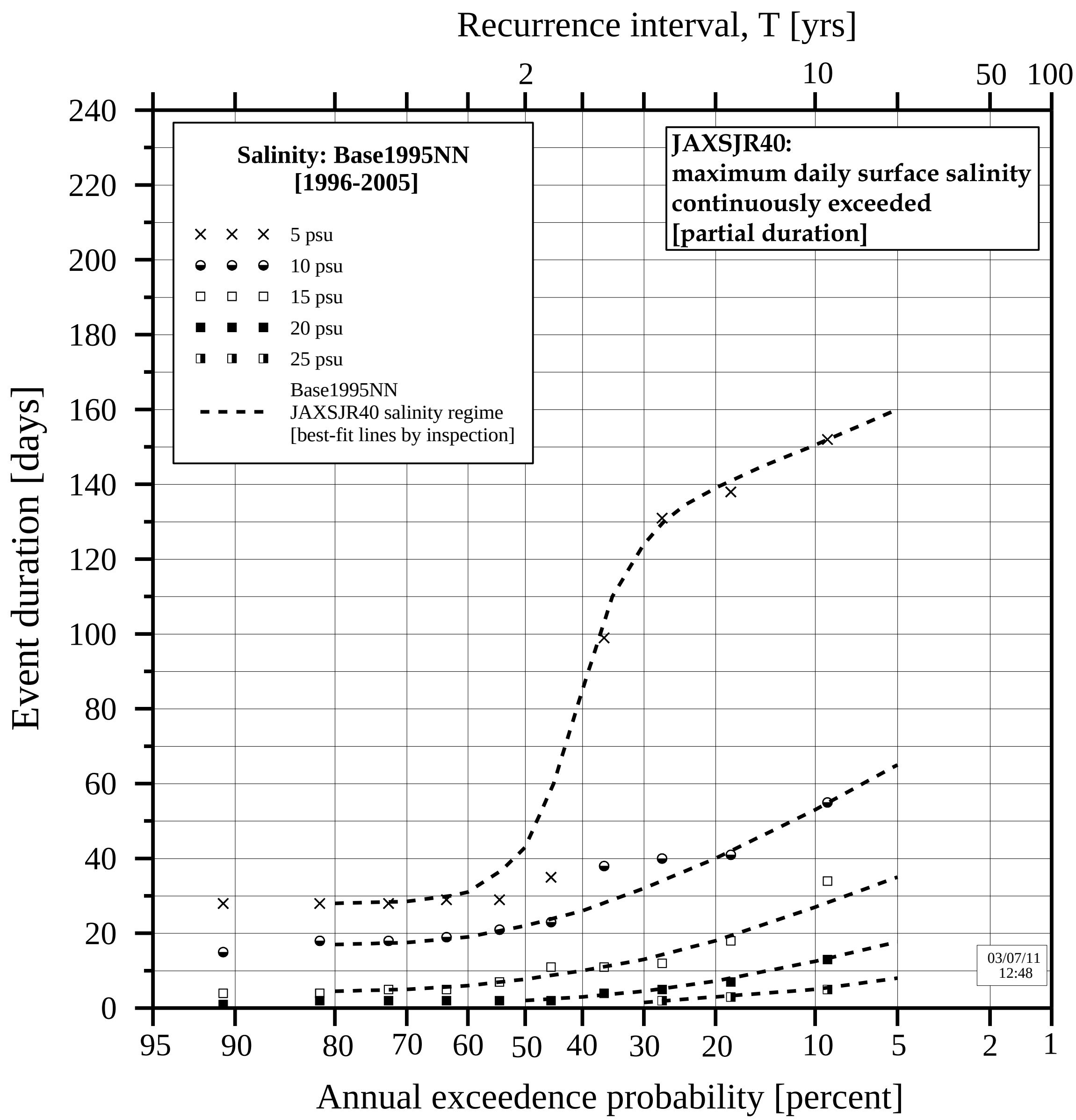



Figure 3. Surface salinity regime for the Base1995NN alternative at JAXSJR40 (daily maximum values)

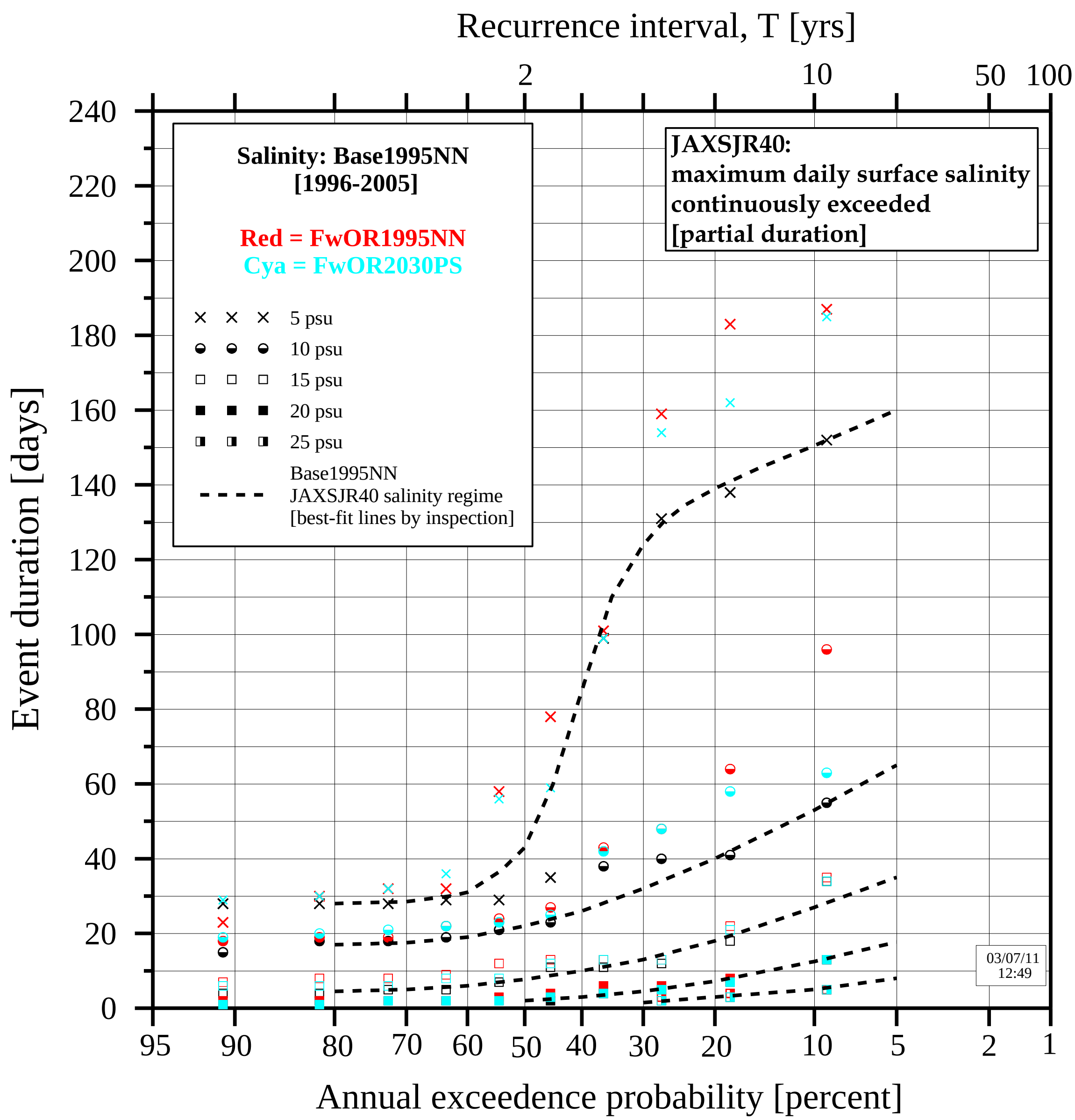



Figure 4. Comparison of surface salinities of different water management alternatives (Base1995NN, FwOR1995NN, and FwOR2030PS) at JAXSJR40

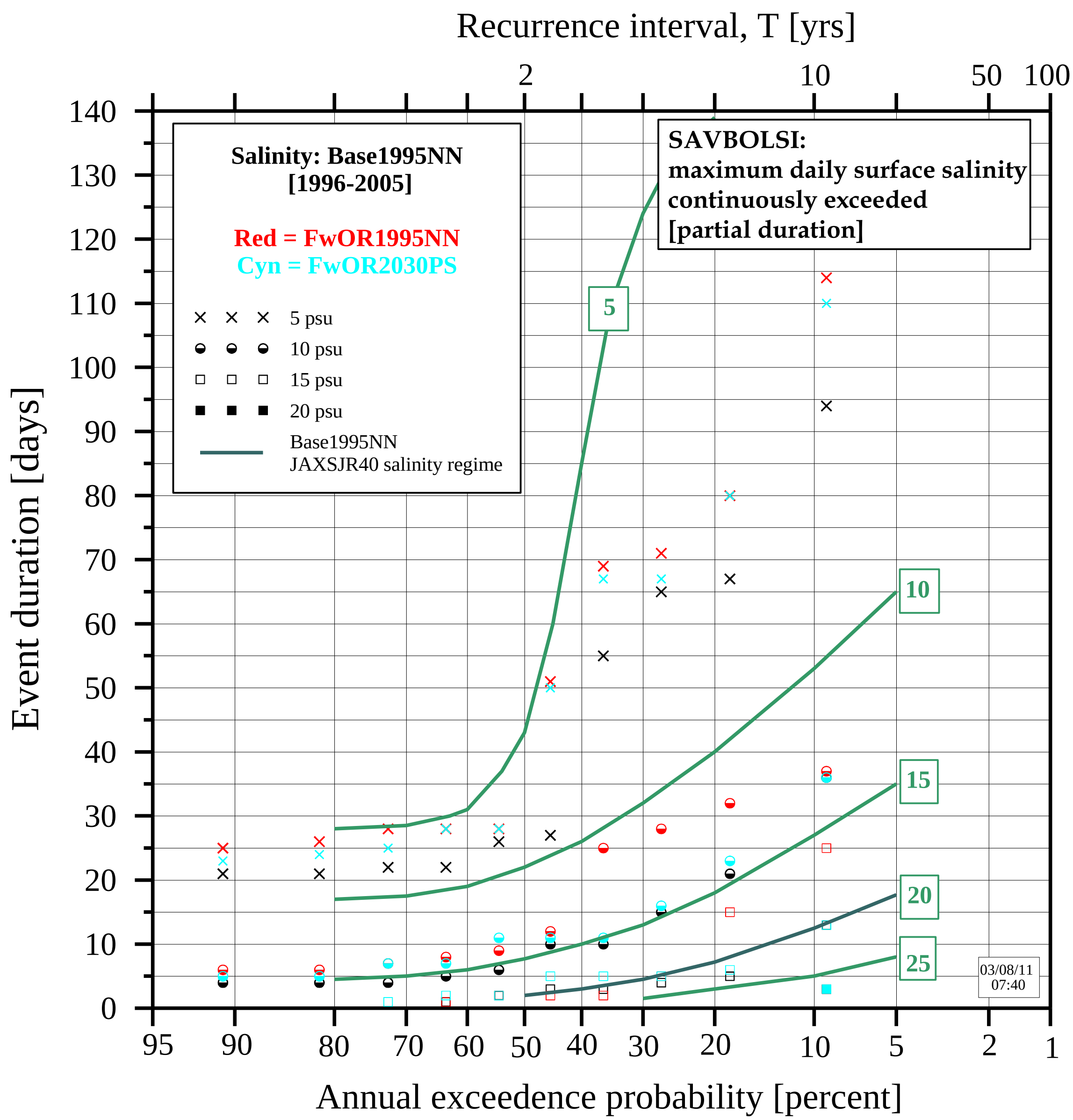



Figure 5. Comparison of salinities for the Base1995NN, FwOR1995NN, and FwOR2030PS alternatives at Bolles School (SAVBOLSI) with the JAXSJR40 salinity regime

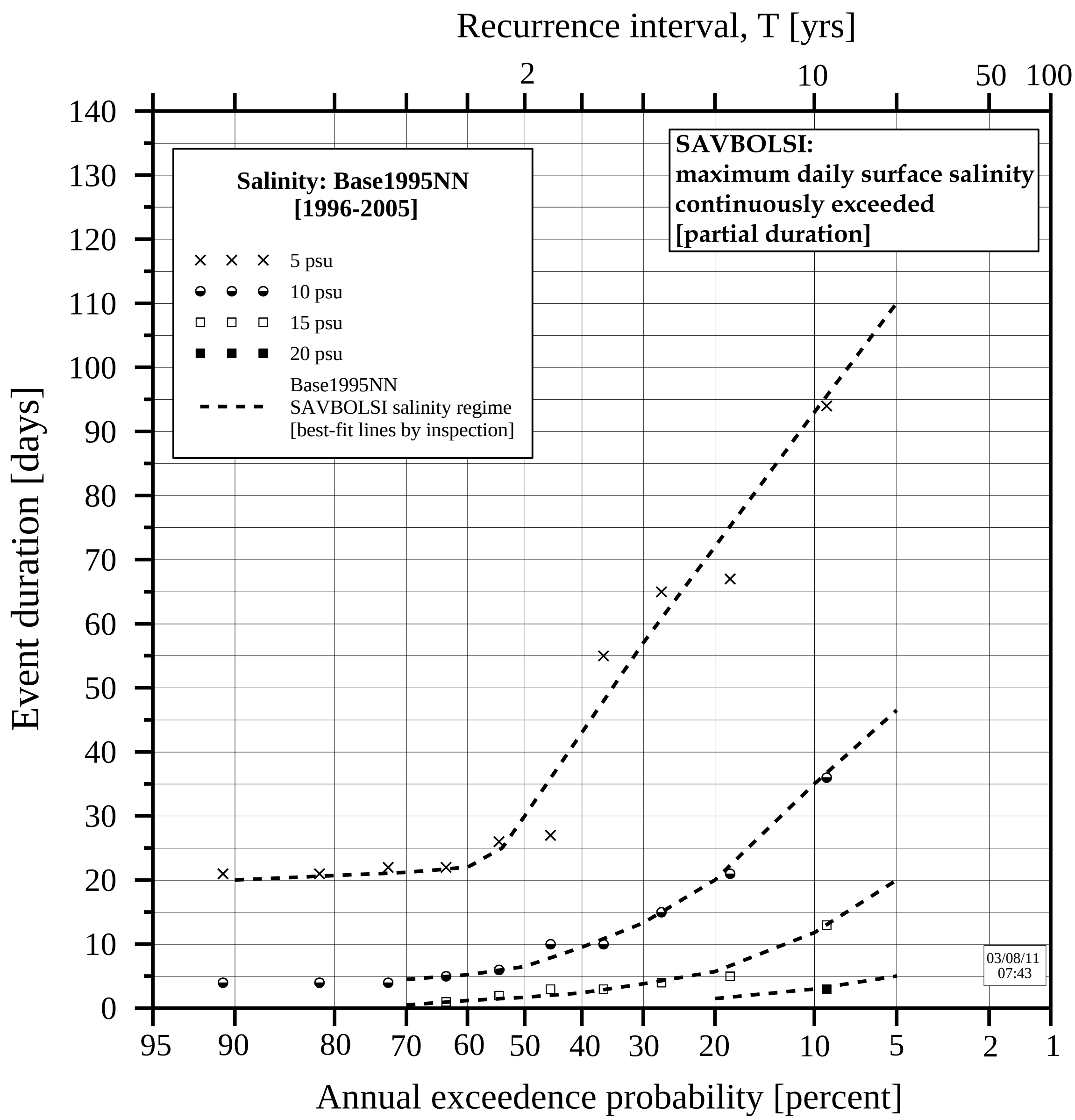



Figure 6. Surface salinity regime for the Base1995NN alternative at Bolles School (SAVBOLSI)

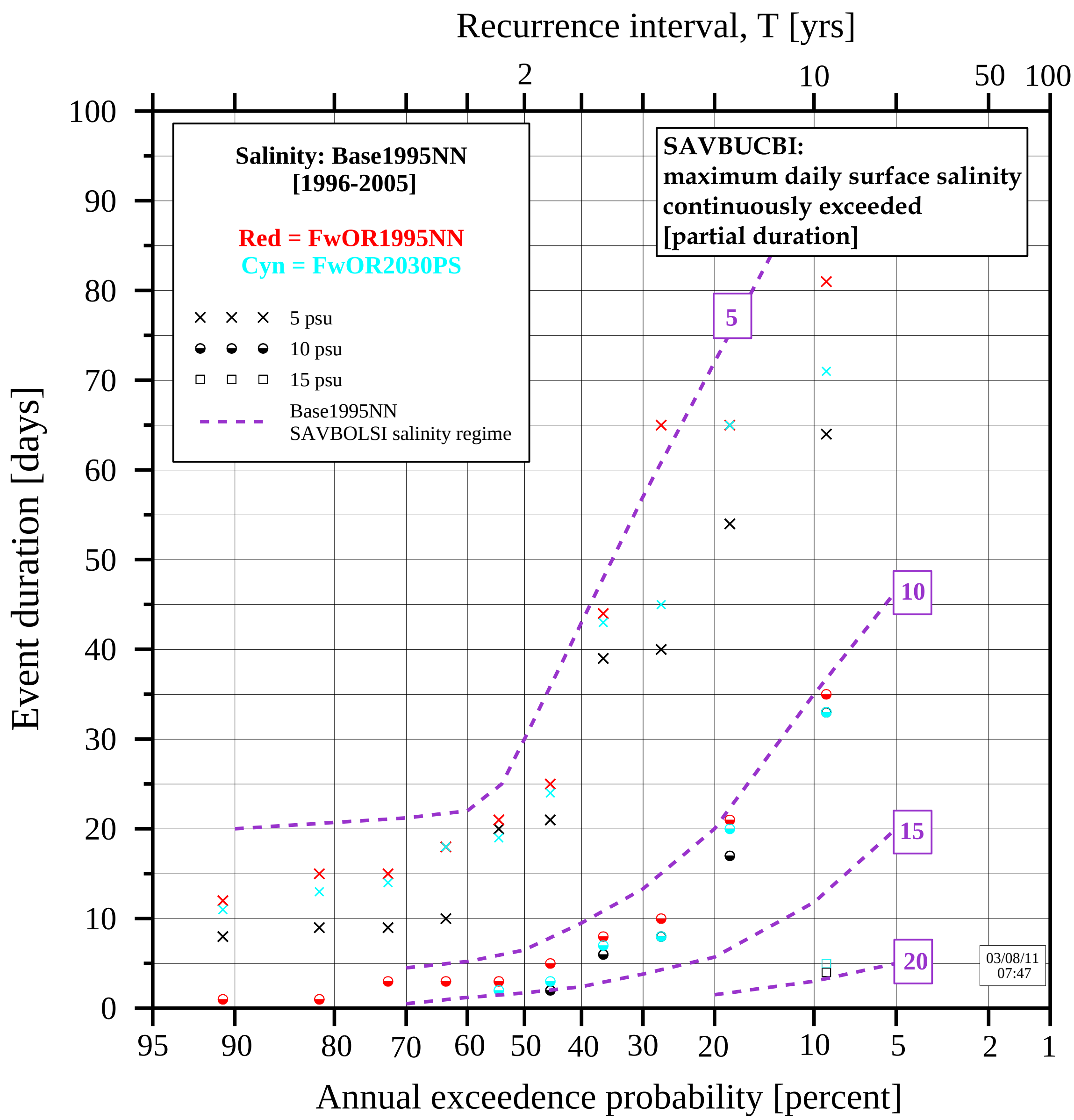



Figure 7. Comparison of salinities for Base1995NN, FwOR1995NN, and FwOR2030PS alternatives at Buckman Bridge (SAVBUCBI) with the Bolles School (SAVBOLSI) salinity regime

Table 1. Modeled SAV station site information

| Site | Modeled Station Name | Location Description |
|---|---|---|
| JAXSJR40 | JAXSJR40 | SJRWMD salinity recorder mid-channel between the Fuller Warren Bridge and Buckman Bridge in Jacksonville |
| Bolles School | SAVBOLSI | SAV monitoring station at Bolles School (east side of river) within the littoral zone grassbed |
| Buckman Bridge | SAVBUCBI | SAV monitoring station at Buckman Bridge within the littoral zone grassbed |

Table 2. Definitions of model scenario acronyms for which modeled salinity data was analyzed with partial-duration frequency analysis at three LSJR SAV monitoring stations

| SAV Monitoring Station | Model Scenario Name | Land Use Year | Withdrawal Type | Upper Basin Project? | Sea Level Rise? | Data | Data Type |
|---|---|---|---|---|---|---|---|
| JAXSJR40 | Base1995NN | 1995 | Baseline: no additional withdrawals | No | No | Surface Salinity | Daily Maximum |
| | FwOR1995NN | 1995 | Full SJR withdrawal + Ocklawaha withdrawal | No | No | Surface Salinity | Daily Maximum |
| | FwOR2030PS | 2030 | Full SJR withdrawal + Ocklawaha withdrawal | Yes | Yes | Surface Salinity | Daily Maximum |
| SAVBOLSI | Base1995NN | 1995 | Baseline: no additional withdrawals | No | No | Surface Salinity | Daily Maximum |
| | FwOR1995NN | 1995 | Full SJR withdrawal + Ocklawaha withdrawal | No | No | Surface Salinity | Daily Maximum |
| | FwOR2030PS | 2030 | Full SJR withdrawal + Ocklawaha withdrawal | Yes | Yes | Surface Salinity | Daily Maximum |
| SAVBUCBI | Base1995NN | 1995 | Baseline: no additional withdrawals | No | No | Surface Salinity | Daily Maximum |
| | FwOR1995NN | 1995 | Full SJR withdrawal + Ocklawaha withdrawal | No | No | Surface Salinity | Daily Maximum |
| | FwOR2030PS | 2030 | Full SJR withdrawal + Ocklawaha withdrawal | Yes | Yes | Surface Salinity | Daily Maximum |

Table 3. Example results of partial-duration frequency analysis for maximum daily surface salinity at SAV station JAXSJR40 (FwOR2030PS)

| Threshold Salinity Value (psu) | Event No. | Start Date | Event Duration (days) | Ranked Event Duration (days) | Probability |
|---|---|---|---|---|---|
| 15 | 1 | 3/11/1996 | 3 | 34 | 9.1 |
| | 2 | 3/25/1997 | 1 | 21 | 18.2 |
| | 3 | 4/11/1997 | 1 | 13 | 27.3 |
| | 4 | 4/15/1997 | 4 | 13 | 36.4 |
| | 5 | 5/29/1997 | 2 | 12 | 45.5 |
| | 6 | 6/7/1997 | 3 | 8 | 54.5 |
| | 7 | 4/13/1999 | 3 | 8 | 63.6 |
| | 8 | 4/25/1999 | 13 | 6 | 72.7 |
| | 9 | 5/11/1999 | 13 | 6 | 81.8 |
| | 10 | 6/8/1999 | 8 | 6 | 90.9 |
| | 11 | 6/19/1999 | 3 | 4 | 100.0 |
| | 12 | 8/31/1999 | 6 | 4 | 109.1 |
| | 13 | 9/15/1999 | 1 | 3 | 118.2 |
| | 14 | 3/19/2000 | 8 | 3 | 127.3 |
| | 15 | 5/15/2000 | 4 | 3 | 136.4 |
| | 16 | 5/28/2000 | 21 | 3 | 145.5 |
| | 17 | 7/3/2000 | 3 | 3 | 154.5 |
| | 18 | 7/8/2000 | 3 | 3 | 163.6 |
| | 19 | 2/19/2001 | 1 | 3 | 172.7 |
| | 20 | 3/8/2001 | 6 | 3 | 181.8 |
| | 21 | 3/19/2001 | 3 | 2 | 190.9 |
| | 22 | 5/1/2001 | 12 | 2 | 200.0 |
| | 23 | 5/15/2001 | 1 | 1 | 209.1 |
| | 24 | 5/17/2001 | 6 | 1 | 218.2 |
| | 25 | 5/25/2001 | 3 | 1 | 227.3 |
| | 26 | 4/6/2002 | 2 | 1 | 236.4 |
| | 27 | 5/6/2002 | 1 | 1 | 245.5 |
| | 28 | 5/20/2002 | 34 | 1 | 254.5 |
| | 29 | 2/2/2004 | 1 | 1 | 263.6 |
| | | | | | |
| 20 | 1 | 3/11/1996 | 2 | 13 | 9.1 |
| | 2 | 4/30/1999 | 5 | 7 | 18.2 |
| | 3 | 5/18/1999 | 2 | 5 | 27.3 |
| | 4 | 9/4/1999 | 1 | 4 | 36.4 |
| | 5 | 9/15/1999 | 1 | 3 | 45.5 |
| | 6 | 5/30/2000 | 7 | 2 | 54.5 |
| | 7 | 6/8/2000 | 3 | 2 | 63.6 |
| | 8 | 3/19/2001 | 1 | 2 | 72.7 |
| | 9 | 5/8/2001 | 2 | 1 | 81.8 |
| | 10 | 5/20/2002 | 13 | 1 | 90.9 |
| | 11 | 6/4/2002 | 1 | 1 | 100.0 |
| | 12 | 6/9/2002 | 4 | 1 | 109.1 |
| | | | | | |
| 25 | 1 | 5/2/1999 | 2 | 5 | 9.1 |
| | 2 | 5/30/2000 | 3 | 3 | 18.2 |
| | 3 | 5/21/2002 | 5 | 2 | 27.3 |