Bar-Built Estuary Modeling

Requested by
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Executive Summary

Background

A multi-agency team partnership, including Caltrans, SCCRTC, Santa Cruz RCD, Santa Cruz County and Swanton Pacific Ranch, is considering a project to restore and redesign the Scott Creek Lagoon Estuary. The project would include examining the existing Highway 1 bridge openings and determining requirements for restoration of the lagoon system as it intersects the roadway. This Preliminary Investigation is needed to ensure that this new project is state-of-the-art in its use of modeling to forecast hydrologic input and output volumes, along with water salinity and expected scour and draining.

To support this effort, CTC & Associates prepared the following Preliminary Investigation. This document addresses only bar-built estuaries, and focuses largely on California, as the type of habitat exemplified by Scott Creek is unique to the state.

To gather this information, CTC & Associates:

- Conducted a literature search on bar-built estuary restoration efforts and research into modeling this type of system.
- Contacted experts to gauge the use of modeling in this kind of system.
- Reviewed existing project documents to better understand the scope of the Scott Creek project and determine whether any of the other restoration projects we researched involved more extensive modeling than what has been performed in planning for the Scott Creek restoration.

Summary of Findings

Modeling of Bar-Built Estuaries

Modeling of small lagoons is a highly specialized field, with a small number of practitioners working on central California coastal environments like Scott Creek. While hydrology modeling is not uncommon (the Trancas Lagoon restoration effort used the national consulting firm Huitt-Zollars), and techniques to model water flow can be transferred from other systems very different from Scott Creek, creating a model that covers both the hydrologic (fluvial and oceanic) and habitat (water quality, channel morphology, specific species needs) realms is more difficult. Our research indicates that this type of modeling is performed only by the organizations we contacted.

Environmental Science Associates (ESA), the consulting firm that prepared the 2012 report *Potential Physical and Biological Implications of Bridge Replacement at Scott and Waddell Creeks* for Caltrans, has conducted modeling for Scott Creek that those we interviewed characterized as exceeding what is typically done for other projects. Those we spoke with said that since every system is different, much of the work done on one project often cannot be leveraged for another. However, ESA is working on a larger-scale model incorporating all of the aspects of lagoon dynamics that is expected to be complete in the next few years.

According to ESA's Bob Battalio, co-author of the 2012 report, while consideration of the ocean environment is often missing from lagoon modeling, this type of modeling is included in the 2012 report on Scott Creek. Mark Stacey of the University of California–Berkeley suggested that a component that may be missing from the work already performed on Scott Creek is consideration of the salt dynamics (how salt enters the system, how it is structured in the lagoon, and how it is flushed out of the system), and said that his graduate students (including Megan Williams) have been studying this with regard to Scott Creek. Another graduate student, Daniel Nylen, who works with John Largier at UC Davis, is working on a master's thesis on Scott Creek's closure history.

The experts we interviewed emphasized the distinction between *numerical modeling* and *conceptual modeling*. Numerical (bottom-up) modeling starts by looking at the basic physics involved in a system. Purely conceptual (top-down) modeling involves considering the history of a system and what other systems it is similar to in order to determine decision procedures for remedying problems. (For example, if fish are dying in one system, the conceptual modeling approach would be to look at similar systems where fish aren't dying and identify ways to make the troubled system more like those.) Conceptual modeling can involve quantitative data (field measurements to provide a more detailed understanding once the concepts involved—the system dynamics—are understood), and there is no clear dividing line between a quantified conceptual model and a numerical model. According to ESA's Dane Behrens, a model that is too complex, with too many degrees of freedom, is likely to be problematic, while at the other end of the spectrum, a conceptual model is a "black box"—a recording of how certain interventions produce certain outcomes without attempting to identify the internal processes that underlie these reactions of the system.

Costs of Modeling

John Largier of UC Davis noted that small lagoons like Scott Creek have not received comprehensive modeling in the past due to prohibitive costs. At Caltrans' request, we specifically looked into modeling at the Pescadero and Trancas Lagoons. Both of these projects are in progress, with no full plan or cost proposal available. We have provided status information, documents and other information about Pescadero, Trancas, Russian River and other systems that our interviewees had worked on or knew about.

Bob Battalio of ESA estimated that modeling of a small lagoon would cost between $50,000 and $100,000, while John Largier (UC Davis) said that a decent modeling project would require $100,000 per year for at least a couple of years. According to Mark Stacey (UC Berkeley), costs would depend on one's concerns in performing the analysis. If the emphasis was on water level, that would cost approximately $50,000 per year. If the scope went beyond water level, the project would cost more.

Gaps in Findings

A complete lagoon model applicable to Scott Creek has not yet been developed. It may be worthwhile for Caltrans to meet with John Largier (UC Davis) or Mark Stacey (UC Berkeley) to more fully communicate the work already done by ESA and get their ideas on additional data collection; Mark Stacey explicitly mentioned adding more robust inundation modeling and salinity dynamics modeling, as his group is working on for Pescadero Creek. Both Mark Stacey's group and Bob Battalio's team are currently involved in creating modeling tools that may be applicable to Scott Creek within the next couple of years.

Next Steps

In developing a final plan for restoring the Scott Creek Estuary, Caltrans may wish to consult the prime interview subjects of this Preliminary Investigation:

- Bob Battalio (ESA) led the work already done on Scott Creek, and had specific ideas on how to continue the work.
- John Largier (UC Davis) may also have insight on how to proceed, and might provide a valuable second opinion to Bob's.
- Mark Stacey (UC Berkeley) likewise might provide valuable assistance given his experience in this field.

Other potential experts to follow up with include:

- Jim Robins, who represents Coastal Conservancy on the Integrated Watershed Program.
- Megan Williams, a graduate student of Mark Stacey's, who just finished her master’s thesis on salt dynamics in the Scott Creek estuary.
- Daniel Dylan, a graduate student of John Largier, who is writing a master's thesis on the closure history of Scott Creek.

Detailed Findings

Modeling of Bar-Built Estuaries

Scott Creek

Summary: An analysis was performed that modeled some aspects of the system. According to Bob Battalio of ESA, “We didn't finish the Scott Creek analysis; restoration upstream needs to be developed and agreed to.” The Integrated Watershed Program (Coastal Conservancy, represented by Jim Robins) is working on multiple upstream restoration projects with Cal Poly.

Potential Physical and Biological Implications of Bridge Replacement at Scott and Waddell Creeks, Bob Battalio (ESA PWA) and Leyla Arsan (SWCA Environmental Consultants), May 2012.
This report provides a baseline of what analysis of the Scott Creek system has already been performed. It is an assessment of possible roadway modifications involving “consideration of historic and existing conditions and development of conceptual models that linked physical changes to ecological function.” Relevant highlights include:

- Section 3.8 (p. 29) includes conceptual models proposed to explain how changes to the bridge configuration could cause ecosystem changes. The models are presented as flow charts listing anticipated restored processes, structural changes and ecosystem response given a specific configuration. For example, a change to bridge length would then lead to improved seasonal/tidal influences in the lagoon (one of five identified restored processes), which would lead to improved water quality and so more favorable conditions for salmon.
- A record of habitat changes in Scott Creek over the last century or more.
- Estimated ecological effects are provided for three scenarios: if no action is taken, if the bridge is replaced under emergency conditions, and if it is replaced as planned in the project scope summary report.
- Appendix A, “Pescadero Creek Flow Frequency Analysis,” was prepared according to the U.S. Geological Survey’s 1982 *Guidelines for Determining Flood Flow Frequency* and its PeakFQ computer program.
- Appendix B, “Wave Transformation Modeling,” analyzes the effect of near-shore wave climate on creek and lagoon mouth changes. The study was performed for Scott Creek and Waddell Creek.
- Appendix C, “Scott Creek Lagoon Water Balance Modeling,” states that “a model of the Scott Creek lagoon was developed to better understand the current state of the lagoon and the implications of alternative bridge configurations on water levels and breaching. First, water balances were conducted separately for open and closed lagoon configurations... to calibrate the model and estimate outflows that were not measured, such as berm seepage and breach channel outflow. ...These losses... were used along with the measured inflows to predict lagoon surface elevation response, which is known to be an important driver of breaching frequency.”
- Appendix C also includes a water balance equation describing how various inflows and outflows influence the lagoon’s water surface elevation (water volume). Surface area

and storage were estimated with the help of a digital elevation model developed using aerial LiDAR surveys. Investigators measured creek inflow, precipitation and evapotranspiration (plus estimated berm seepage). Creek outflow (when the lagoon is in the open configuration) was calculated via Manning's open-channel formula, which uses the measured size, slope and roughness of the channel.

- Appendix F, "Field Data," contains measurements of Scott Creek water levels and temperature.
- Appendix G, "Scott Creek Time Series" presents more data: water elevation, total water level, discharge and salinity.
- Appendices I and K give maps and species lists.
- Appendix L, "Habitat Equivalency Analysis Model—Methods, Rationale, and Results," was "used to assess and compare the potential biological effects of conceptual bridge alternatives."

Implications of Highway Bridge Crossing Effects on Coastal Lagoons: Assessment of the Effects of Highway 1 Bridges on Scott and Waddell Creek Lagoons, Santa Cruz County, HDR Engineering, prepared for Caltrans, November 2008.
ftp://san-andreas-land-conservancy.org/pub/CNRCC_links/Implications%20Hwy-1%20Bridge%20Crossings%20081117.pdf
This document provided the impetus for the ESA study that culminated in the 2012 report above. In addition to the information specifically about Scott Creek, it provides an overview of lagoon dynamics and the actions that affect them.

Interviews:

- **Bob Battalio** (ESA) emphasized the importance of the ocean-side modeling already performed. What was created for Scott Creek was a quantified conceptual model of lagoon hydrology and other measures. He mentioned that in the creek's natural state, there are a lot of little side channels for fish to mature in before they go out to sea with the first rain in October. This rearing habitat needs restoration. ESA is already looking to start a new study with the Santa Cruz County Resource Conservation District to spend more time looking at the creek mouth to confirm that they can quantify how it changes. David Revell has been working with local stakeholders on ESA's behalf to initiate this study.
- **John Largier** (UC Davis) noted that his graduate student Daniel Nylen is currently working on a master's thesis that involves the closure history of Scott Creek.

Pescadero Creek

Summary: A science panel (http://www.parks.ca.gov/?page_id=27304) is studying this system to make specific recommendations. The panel's report was scheduled for completion in 2014 but will likely take longer. No numerical modeling is planned for the restoration.

Interviews:

- **John Largier** (UC Davis) heads the (unfunded) science panel. He stated that the current studies there are more conceptual and data-based, with no real modeling at all. They're reviewing what work has been done and what is known about the system. Their goal is like a conceptual model, but is not quantified. It's an active management situation.

- **Mark Stacey** (UC Berkeley) is on the science panel, but is also doing work that is somewhat independent of it. He has two graduate students focused on data collection at the site, and working toward a computational, predictive model of salt dynamics (Megan Williams' dissertation on this topic is referenced under "Literature on Bar-Built Estuaries" below). He explained that they are working on an inundation model, covering inundation, flow and sediment in the system in response to changing mouth conditions or restoration activities. There is talk of redredging channels, so they need to determine whether these channels will just be filled back in with sediment over time. Stacey's group is doing this with a Deltarez family of model (which used to be called Delft3d-FLOW; the user manual can be read at https://www.rsmas.miami.edu/users/prynne/Tidal_Inlet_files/Delft%203D%20Flow%20Manuel.pdf); this is a tool with a wide user base that is testing all its components. Once Stacey's group builds a particular implementation of it, "the modules are plug and play." In other words, the underlying model is sound, but components need to be built on top of it in order to play out hypothetical scenarios in the system.
- **Bill Stevens** of NOAA is not involved in the current science panel that is devising long-term solutions for the system, but is familiar with the history of the system dating back to the mid-1990s when the Pescadero bridge was modified and State Parks did some restoration in the lagoon. This caused the schedule for mouth opening to change, and there have consequently been 14 years of fish kills. Stevens was involved in a manual breach of the sand bar in 2012 to address this for the season, which seemed to help. The mouth was manually opened and the water quality monitored to see if future action should be taken (none was taken; the mouth reclosed by itself).
- **Bob Battalio** (ESA) said that work for Pescadero Creek is more focused on problems happening upstream than Scott Creek. He said many regulators frown at the sort of mechanical intervention that Bill Stevens described above.

Trancas Lagoon

Summary: This restoration is in the analysis stage. Conceptual modeling was performed by Huitt-Zollars. Cost and next steps are still to be determined, but the project team is aiming for completion of the restoration by 2019.

Conceptual Hydrology Analysis for Trancas Creek and Lagoon, Randy Chapman, Huitt-Zollars, expected January 2014.
This report will be a conceptual drainage analysis of the drainage tributary to Trancas Creek, including stormwater flow rates and hydraulic flow patterns for the creek based on existing topography and infrastructure with projections of changes from the removal of fish passage barriers. Key concerns are fish passage and flood control functionality, and investigators are of the opinion that the project can proceed using largely the methods established for past Los Angeles River and Malibu Creek projects, which did not involve enabling fish passage as a primary goal. Modeling for the existing and proposed conditions will employ HEC-RAS methodology.

A news article interviewing Dagit ("Lagoon Restoration Sought at Trancas Creek," Jimy Tallal, *Malibu Times*, August 21, 2013) can be found at http://www.malibutimes.com/news/local/article_1aa978cc-0a21-11e3-9d79-0019bb2963f4.html.

Interviews:

- **Rosi Dagit** said that the choices in modeling approach reflect agency requirements: Standard HEC-RAS models meet Los Angeles County and Caltrans requirements, while a fish crossing analysis was done per directives from jurisdictional wetlands using the California Rapid Assessment Method.

Russian River

Summary: ESA is involved in an ongoing effort to restore the Russian River in Sonoma County, which will involve similar activities and challenges as the work being considered for Scott Creek.

Episodic Closure of the Tidal Inlet at the Mouth of the Russian River – A Small Bar-Built Estuary in California, Dane K. Behrens, Fabian A. Bombardelli, John L. Largier, Elinor Twohy, *Geomorphology* 189, pages 66-80, 2013.
Citation at http://www.sciencedirect.com/science/article/pii/S0169555X13000548
This paper analyzes 60 years of daily closure records for the Russian River mouth and discusses and augments a model to evaluate the various influences on mouth closure.

Modeling Restoration Scenarios in a California Bar-Built Estuary, Dane K. Behrens, *30th Annual Salmonid Restoration Conference* brochure, page 119, 2012.
http://www.calsalmon.org/files/documents/conference/Conference2012Proceedings.pdf
This short presentation summary discusses modeling difficulties for the Russian River mouth. It describes how the use of many existing conceptual and quantitative models for closure is precluded by rapid morphological change, unsteady freshwater inputs, and difficulties in scaling well-established inlet relationships in these smaller systems (i.e., bar-built estuaries with relatively small—cross sectional area less than 100 m^2—and shallow tidal inlets).

The Influence of Freshwater Inflows in California Coastal Lagoons, Dane Behrens, CERF, 2013.
Included as Appendix B (provided by ESA).
This presentation document discusses quantified conceptual modeling of California lagoons, including the Russian River and smaller lagoons, and covering climate change impacts and tidal prism size.

Interviews:

- **John Largier** stated that this project involved no modeling, and no simulation of the physics involved. Dane Behrens, Matt Brennan and Largier did create a numerical model of stratification and circulation of water movement; i.e., the lower layer of sea water that becomes trapped. This did not come close to representing an ecosystem.

Other Central California Lagoon Systems

Bob Battalio, Dane Behrens and John Largier all shared some information about other projects they had worked on. While some of the projects that ESA worked on did involve some modeling, none of these—according to Bob Battalio—were as extensive as what ESA has already performed for Scott Creek, or involved procedures that would be appropriate for Scott Creek. Some of these included:

- Salmon Creek in Bodega Bay involved some monitoring, but no models. A NOAA summary of the project can be found at http://www.noaa.gov/features/resources_0908/salmoncreek.html.

- Carmel Lagoon was modeled with regard to hydrologic and geomorphic patterns of estuary breaching and closure for the Ph.D. thesis of Andrew Rich (2013). An abstract can be found at http://www.geol.ucsb.edu/news/event/460.
- Crissy Field Park wetland restoration involved an estuary restoration that ESA worked on. An overview of the full project can be found at http://www.nps.gov/partnerships/rest_crissy_field.htm. A paper by Bob Battalio, "Predicting Closure and Breaching Frequencies of Small Tidal Inlets—A Quantified Conceptual Model," that uses this project as an example is discussed below.
- Mission Creek Lagoon on the Santa Barbara waterfront. ESA's summary of this project can be found at http://www.esassoc.com/projects/mission-creek-lagoon-and-laguna-channel-restoration-conceptual-design.
- Arroyo Grande Creek. Information about an overall endangered steelhead recovery plan that appears to include this restoration can be found at http://lpfw.org/steelhead-recovery-plan.
- Waddell Creek is covered in the 2012 ESA report on Scott Creek, as the anticipated replacement of the Highway 1 bridge that prompted this study will also affect Waddell Creek.
- ESA is looking at future projects on the San Lorenzo River in Santa Barbara, Los Pensequitos, Attos Creek on Northern Monterey Bay and Santa Ynez on Vandenberg Air Force Base.
- We have provided a list of papers by John Largier and his students about estuary systems similar to Scott Creek as Appendix A.

Southern California Lagoon Systems

Apart from Trancas Lagoon, this area was not included in the project scope due to differences in species and other environmental factors from Scott Creek, but we have described below a foundational paper about conceptual modeling from David Jacobs (UCLA), who has done extensive historical analyses of estuaries along the whole California coast. There has likely been some estuary modeling activity in this region, though specifics were not confirmed for this report. Based on our conversation with Jacobs, it appears that the state of practice in lagoon restoration is significantly behind that practiced in more northern parts of the state.

Bob Battalio said that he thought hydrologic modeling had been done by SANDAG without substantial benefit. According to Lesley Ewing of the California Coastal Commission, this was likely for the I-5 widening project (described at http://www.gsws.com/email/Sandag/downloads/SAN-I5-CLIP-NCT-Buena-Vista-Lagoon.pdf); however, this was not so concerned with bar-built estuaries.

Lesley Ewing said he was not aware of any modeling occurring in any southern California projects, but suggested that Caltrans District 11 staff might have more information. David Jacobs was also unaware of any such modeling occurring.

Malibu Lagoon Restoration and Enhancement Project, Mark Abramson, Rosi Dagit, et al., Santa Monica Bay Restoration Foundation, 2013.
http://santamonicabay.org/wp-content/uploads/2014/05/Malibu-Lagoon_Comprehensive-Monitoring-Report.pdf

This project (like Trancas, involving Rosi Dagit), describes a 2012 restoration involving excavation of 12 acres in the western half of the lagoon and removal of the berm, and describes specifically the data that was collected before and after this restoration to monitor the system.

These articles were recommended by David Jacobs as representing some of the bar-built lagoon modeling work that has been done in Southern California. As they are somewhat beyond the scope of this Preliminary Investigation, we have not included the full articles as appendices, but they are available upon request.

Effect of a Small Southern California Lagoon Entrance on Adjacent Beaches. M.H.S. Elwany, R.E. Flick, M.M. Hamilton, *Estuaries*, Vol. 26, No. 3, pages 700-708, June 2003.
Citation at
http://www.jstor.org/discover/10.2307/1353530?uid=3739976&uid=2&uid=4&uid=3739256&sid=21104619784097
This paper considers the effects of natural and artificial openings of the small San Dieguito Lagoon on the adjacent barrier beach.

Characteristics, Restoration, and Enhancement of Southern California Lagoons. M. Hany, S. Elwany, *Journal of Coastal Research*: Special Issue 59 - Proceedings, Symposium to Honor Dr. Nicholas Kraus: 246-255. 2011.
This paper discusses monitoring lagoons in light of environmental impacts to better understand the system, particularly regarding physical parameters such as tidal flushing, water quality, freshwater flow reduction, and channel and basin sedimentation.

Australia

The scope of this Preliminary Investigation included some research into modeling activities in Australia, as the ecology is somewhat similar to central California. John Largier and David Jacobs both confirmed that activity in this region has significantly added to scholarship in this area. Citations provided by Jacobs include the following (not included with this document but available upon request), which focus on the hydrodynamics involved, and not on species preservation:

Morphometric Assessment of Intermittently Open/Closed Coastal Lagoons in New South Wales, Australia, P.E. Haines, R.B. Tomlinson, B.G. Thom, Estuarine, *Coastal and Shelf Science,* Volume 67, Issues 1–2, March 2006, Pages 321–332.
Citation at http://www.sciencedirect.com/science/article/pii/S027277140500404X.
Provides an assessment framework for lagoon sensitivity based on its physical geometry, demonstrated using eight examples from the New South Wales area.

A Morphodynamic Model to Simulate the Seasonal Closure of Tidal Inlets, Roshanka Ranasinghe, Charitha Pattiaratchi, Gerhard Masselink. *Coastal Engineering*, Volume 37, pages 1–36, 1999.
Citation at http://www.sciencedirect.com/science/article/pii/S0378383999000083.
This study developed a dynamic, morphological model simulating the seasonal closure of inlets.

Also, conceptual model diagrams of wave-dominated estuaries (the Australian term for bar-built estuaries) and related discussion can be found at
http://www.ozcoasts.gov.au/conceptual_mods/geomorphic/wde/wde.jsp.

Additional Insights Gained from Interviews

This section covers facts and observations about estuary modeling that came out of interviews and have not already been discussed above with respect to specific projects.

Bob Battalio (ESA) shared observations including the following:

- He contrasted the kind of robust modeling involved in Scott Creek with traditional modeling, which is more of a decision tree based on data that has been collected.
- One of the complexities involved with modeling this kind of system is that each state—open, closed and intermediate—involves a different set of equations. When a lagoon is closed, one can create a water balance model (this was done for Scott Creek for the 2012 report) based on what's coming in and solve for berm seepage.
- Water balance modeling can be done simply with quasi-dynamic measurements (a series of time steps) or can involve more detailed monitoring.
- In the kind of hydrologic model performed for SANDAG Highway 5 and the Coastal Commission, simplifying assumptions are used instead of measurements (e.g., assume some conditions at the mouth of the estuary, and run the model). But because berm conditions change almost hourly, to really understand the system, you have to look at its dynamic state, at the beach geometry, and terrain at different elevations. Physical models such as the HEC-RAS model (http://www.hec.usace.army.mil/software/hec-ras/) won't work across the range of conditions.
- ESA assisted Washington State DOT in developing water crossing road design guidelines. See pages 232-249 of http://wdfw.wa.gov/publications/01501/wdfw01501.pdf.

John Largier (UC Davis) stressed that the sort of all-purpose, quantified lagoon model being sought by ESA isn't the only kind of useful model, and depending on budget may not be needed to achieve desired effects; he noted that this is not the approach that is being pursued for Pescadero Creek. Ideally, modeling should be a collaboration among people who build structures and are concerned with specific species. Largier said there are many environmental consultants who can perform hydrologic monitoring; however, classical consulting engineers tend not to have an appreciation of how physical aspects connect to ecological aspects. He noted that many systems have been damaged by "restorations."

Mark Stacey (UC Berkeley) said that with regard to the work his team is doing for Pescadero Creek (described above), while the funding for this project is focused on Pescadero, the tool is being built in a more general way to allow it to be used on other similar small lagoons along the Pacific coast. The inundation component will be completed this year, and a module dealing with sediment will be built in 2015 and usable by the middle of the year. Regarding modeling generally, he said that the ecosystem side of it should be a layer on top of the kinds of hydrologic models that they're discussing. Stacey said there is a community of practitioners that think about those interactions, but he noted that the environmental and hydrologic sides can be decoupled, and he suggested it might be valuable to do that because the degree of transferability will be very different between those different layers.

David Jacobs (UCLA) says that while they're very interested in the dynamics of these systems, our understanding of them is pretty limited, and that given the rapidly changing state of such systems, the idea of an accurate predictive model is "a dream."

Literature on Bar-Built Estuary Modeling

Literature not specific to any of the projects mentioned above is listed here. Citations were collected based on relevance to Scott Creek modeling, and provide a sampling of the various approaches to modeling taken in this area.

In addition to those articles described here, see Appendix A for more articles by interviewee John Largier, most of whose work is relevant to this effort.

Classification of California Estuaries Based on Natural Closure Patterns: Templates for Restoration and Management, David Jacobs, Eric D. Stein and Travis Longcore, Southern California Coastal Water Research Project Technical Report 619, August 2010.
http://www.usc.edu/org/seagrant/Publications/PDFs/TR%20619%20Estuarine%20classification%20for%20restoration%20design_FINAL.pdf
This resource provides a foundation for understanding estuary conceptual modeling. To determine the best design template for a wetland restoration, the authors recommend starting from a classification system "based on an understanding of the processes that formed the estuaries and thus define their pre-development structure." The system developed "uses geologic origin, exposure to [marine] processes, watershed size and runoff characteristics as the basis of a conceptual model that predicts likely frequency and duration of closure of the estuary mouth" (page i).

Hydrological Changes and Estuarine Dynamics, P.A. Montegna et al., 2013.
http://www.springer.com/cda/content/document/cda_downloaddocument/9781461458326-c2.pdf?SGWID=0-0-45-1355458-p174672971
Chapter 2, "Conceptual Models of Estuary Systems," lays out the changes of altered inflows in estuaries, providing a "conceptual model." The paper also discusses tides and water column effects: salinity, sediments, nutrients and biological indicators (i.e., species that integrate changes in the environment and so can indicate changes or stability in the estuary).

A Hydrologic and Geomorphic Model of Estuary Breaching and Closure, Andrew Rich, Edward A. Keller, *Geomorphology* 191, pages 64-74, 2013.
Citation at http://www.sciencedirect.com/science/article/pii/S0169555X13001153
This paper documents a model incorporating estuary hydraulics and the geomorphology of the inlet system.

Predicting Closure and Breaching Frequencies of Small Tidal Inlets—A Quantified Conceptual Model, Bob Battalio, Don Danmeier and Phil Williams, 2006.
http://www.esassoc.com/sites/default/files/ICCE2006_Battalio.pdf
This paper describes the quantified conceptual modeling (QCM) process, and how it is a "top down" combination of "bottom up" models and field data used to quantify lagoon and estuary hydrology and is useful to inform management and assess project alternatives, as with Scott Creek. The paper documents a conceptual model of processes affecting inlet dynamics to quantify closure and breaching criteria. Key parameters in the model include wave conditions (wave power and wave run-up), tidal conditions (source tide, lagoon volume, tide range and power), and inlet morphology (e.g., berm elevation).

Using New Methodologies to Assess Bar-Built Estuaries Along California's Coastline, Ross Clark, Cara Clark, et al. Central Coast Wetlands Group, November 30, 2013.
http://ccwg.mlml.calstate.edu/sites/default/files/documents/BBE_Assessment_report.pdf
This document is focused on bar-built estuary management and includes some discussion of modeling. Page 5 includes a diagram outlining a conceptual model of natural inputs and outputs of water and sediment, stressors and their effective processes, nutrients, and bar-built estuary responses. Page 18 describes the different levels of wetland monitoring and assessment developed by the USEPA and the California Rapid Assessment Method (CRAM).

Measuring Key Physical Processes in a California Lagoon, Brendan De Temple, Bob Battalio, James Kulpa, Proceedings of the Conference, American Society of Civil Engineers, pages 133-147, 1999.
Introduction at http://eurekamag.com/research/018/423/018423322.php
This report provides background about field data collection, including beach geometry and the waves and water levels that affect the beach, and consequently the whole system.

Hydrodynamics and Salt Dispersion in Intermittently Closed Bar-Built Estuaries, Megan E. Williams, dissertation for University of California, Berkeley, expected publication in spring 2015.
As mentioned in the section on Pescadero Creek above, Williams has been working with Mark Stacey on analysis of salinity in Pescadero Creek. While this document will cover those observations, it will also provide more generalized information about tidally discontinuous estuarine hydrodynamics, estuarine dispersion, and bar-built estuarine response to tsunamis. Per Stacey's recommendations, some of her work could be applied to Scott Creek.

Contacts

The following individuals provided information via phone and/or email in support of this Preliminary Investigation and are available for follow-up questions.

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Appendix A

This Appendix presents a brief bibliography of relevant additional research by John Largier and his students.

Largier, J. L., 1986.
Structure and mixing in the Palmiet Estuary, South Africa.
South African Journal of Marine Science, 4, 139-152.

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The dynamics of tidal intrusion, retention and removal of seawater in a bar-built estuary.
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The stratified hydrodynamics of the Palmiet - a prototypical bar-built estuary.
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In: Estuarine Fronts – Hydrodynamics, Sediment Dynamics and Ecology. J.L. Largier (editor). Estuaries, 16(1), 1-11.

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Changes in estuarine water quality in response to a freshwater flow event.
In: Changes in Fluxes in Estuaries: Implications from Science to Management, K. R. Dyer and R. J. Orth (editors), Olsen & Olsen, Denmark, 74-81.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, E. Twohy, 2009.
Characterization of time and spatial scales of a migrating rivermouth.
Geophysical Research Letters, 36, L09402, doi:10.1029/2008GL037025.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, and E. Twohy, 2013.
Episodic closure of the tidal inlet at the mouth of the Russian River – a small bar-built estuary in California.
Geomorphology, http://dx.doi.org/10.1016/j.geomorph.2013.01.017

Behrens, D. K., F. A. Bombardelli, J. L. Largier, 2014.
Salinity intrusion during the closure phase of a bar-built estuary with irregular bathymetry.
Estuaries & Coasts (in review).

Nylen, B. D., 2014.
Mouth closure dynamics and dissolved oxygen responses in a prototypical small, bar-built estuary: Scott Creek, California.
MS Thesis, Hydrologic Sciences, UC Davis (in review/examination).

Hewett, K. M., 2014.
Dissolved oxygen in the Russian River Estuary: observations and models.
MS Thesis, Environmental Engineering, UC Davis (in preparation)

Largier, J. L. et al, 2014.
Report of Pescadero Lagoon Science Panel.
To be submitted to California State Parks, California Fish & Wildlife, US Fish & Wildlife and NOAA/NMFS.

The Influence of Freshwater Inflows in California Coastal Lagoons

APPENDIX B

Dane Behrens, PhD, ESA PWA

With Bob Battalio, PE, David Revell, PhD, Matt Brennan, PhD, Christina Toms, Louis White, PE, Elena Vandebroek, PE, Philip Williams, PhD, PE, Andy Rich, PhD

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Overview

- **California Lagoons**
- **Impacts of Freshwater Inflow: Observations**
- **Climate Change Impacts**

- **Modeling the Influence of Freshwater Flows**

- **Impacts of Freshwater Inflow: Model**
  - ***Russian River Estuary***
  - ***Smaller lagoons***

- **Synthesis**

California Lagoons

Californiacoastline.org

ESA PWA

Influence of Freshwater Inflow: *Observations*

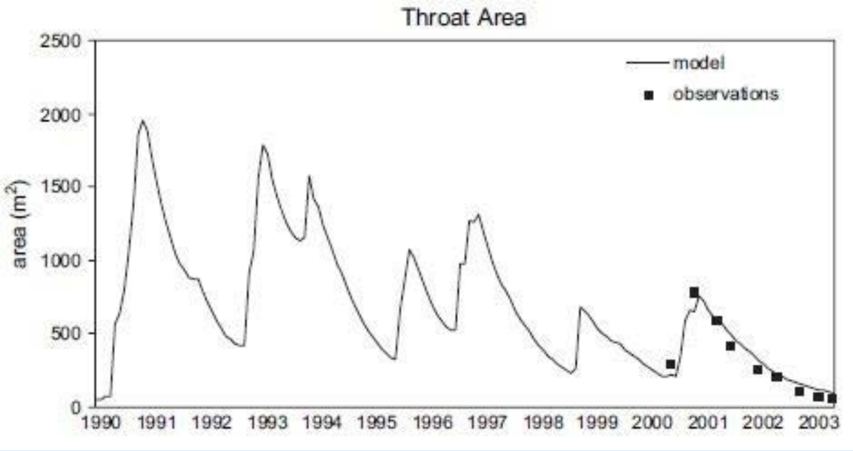
Influence on mouth closure

Small Lagoons (small tidal prism)

- **Freshwater inflows can dramatically change inlet velocity**

Large Lagoons (large tidal prism)

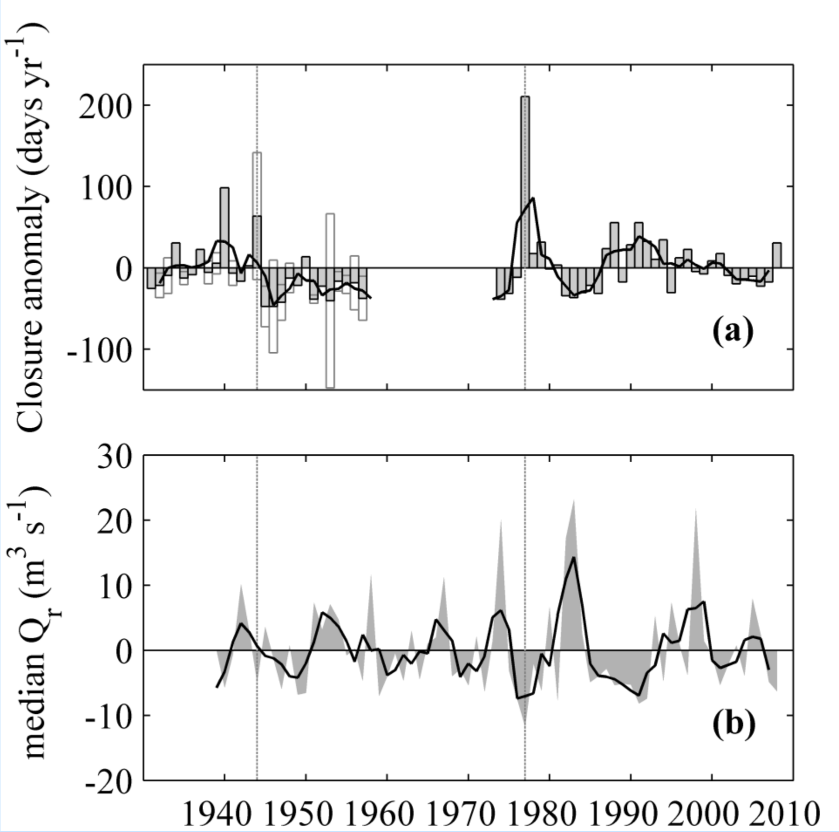
- **Contribute to ebb tide velocity**
- **Less influence on state of the mouth during low/moderate inflows**
- **Major floods may have large impact**



Shuttleworth et al. 2005

Influence on breaching

- **Inverse relation between freshwater inflows and closure duration**

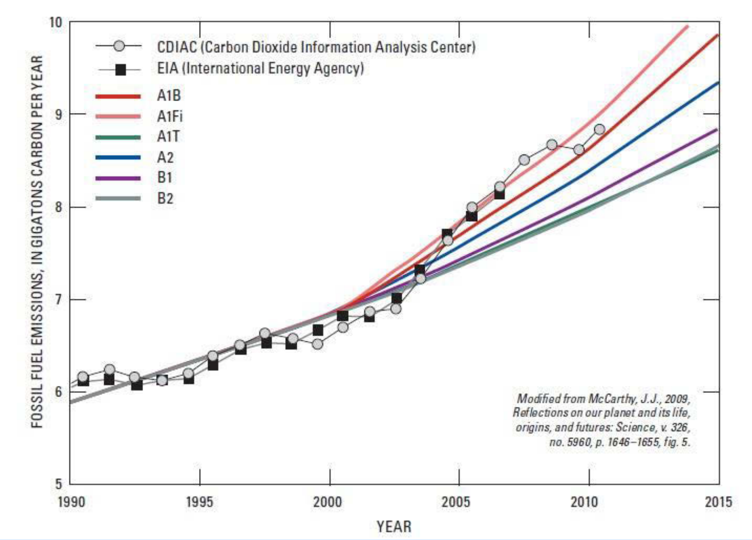


Behrens et al. 2013

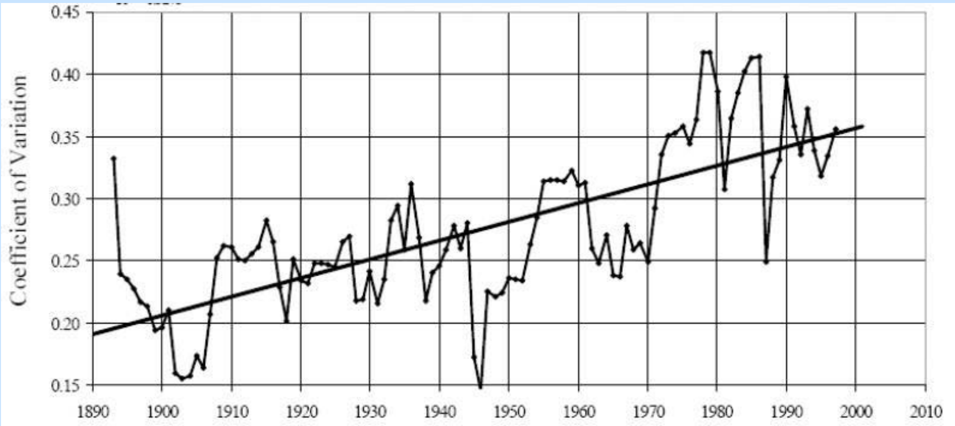
Climate Change Impacts

- **Potential CA changes (Flint and Flint 2012)**
  - **Longer and drier summers regardless of precipitation trend**
  - **Greater variability in precipitation**

- **Climate change rapid from 2000-2010 - Some changes already evident**
  - **earlier springtime snowmelt**
  - **increased numbers of extended dry periods**



McCarthy (2009)



DWR (2006)

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Climate Change Impacts

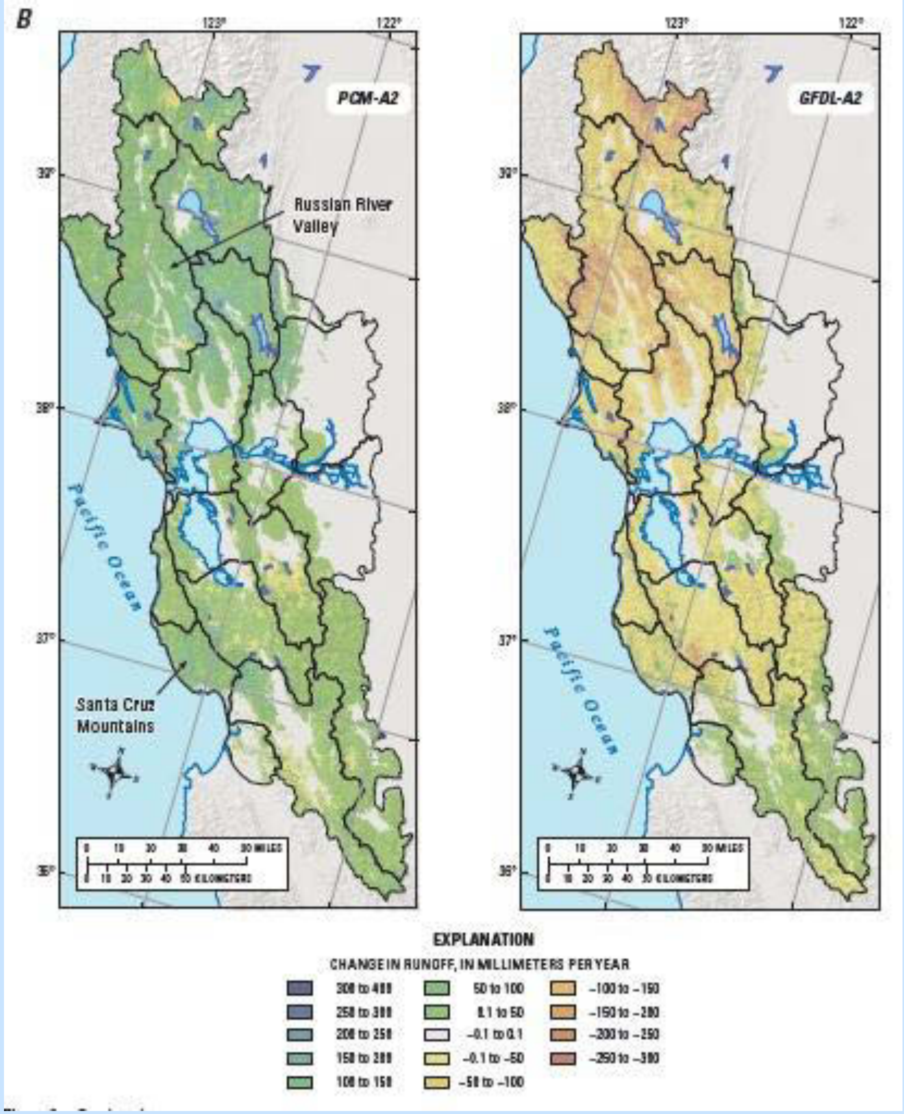
GCM downscaling

- **Temperature and precipitation trends downscaled using statistical techniques**
- **Two emission scenarios**
  - **A2: “medium-high” emissions**
  - **B1: “low” emissions**
- **Calibrated to 17 stream gage locations**

Potential Trends

- **Models differ in results**
- **Shift in peak Jan to Feb**
- **Less fall (Oct-Nov) and spring (Apr-May) precipitation**
- **ET increases**

Parallel Climate Model | **NOAA CM2.1 Model**



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Lagoon Modeling Approaches: Theoretical

Goal:

Determine how changes in precipitation may influence CA lagoons

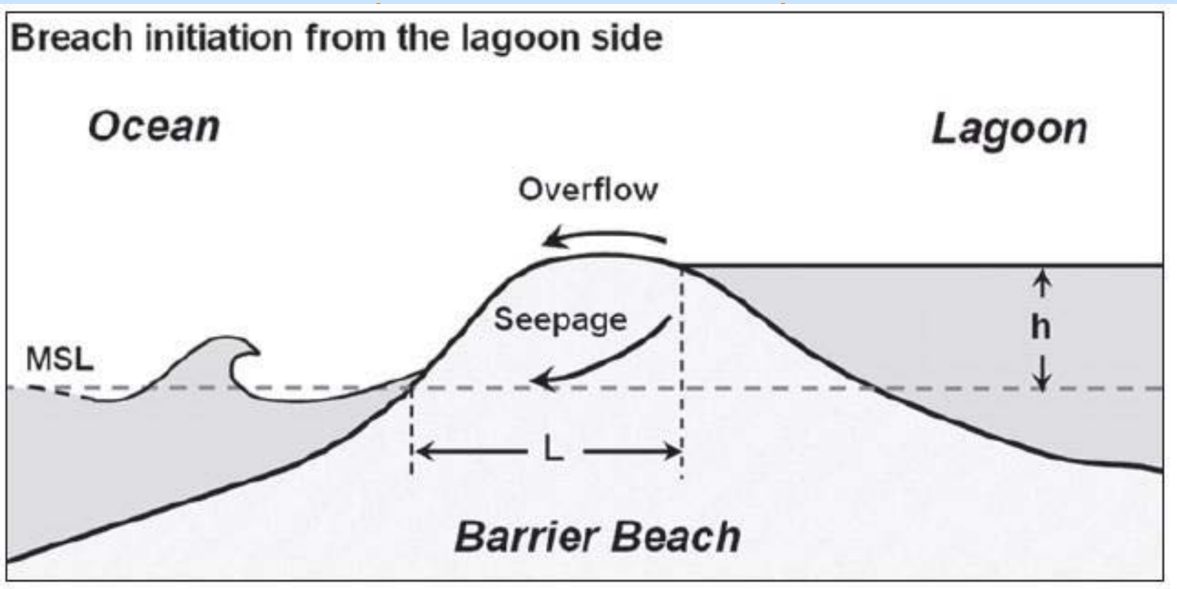
-How do we examine this?

Modeling Approache: *Quantified Conceptual Model*

Lagoon-inlet hydrodynamics
- **Water mass balance model for lagoon**
- **Inlet flows from 1D momentum or empirical**
- **Inlet geometry from empirical relations**

Sediment transport
- **Inlet thalweg allowed to accrete/erode**
- **Sedimentation from wave action**
- **Erosion from channel hydraulics**

Coastal processes | **Beach/Inlet processes** | **Water mass balance**



Kraus et al. 2008

Lagoon Modeling Approaches: *Quantified Conceptual Model*

Development

- Goodwin (1996)
- Battalio et al (2006)
  - Crissy Field
- Rich and Keller (2012, 2013)
  - Carmel River
- ESA PWA (2010-2013)
  - Scott Creek
  - Devereux Slough
  - Mission Creek
- Today
  - Russian River

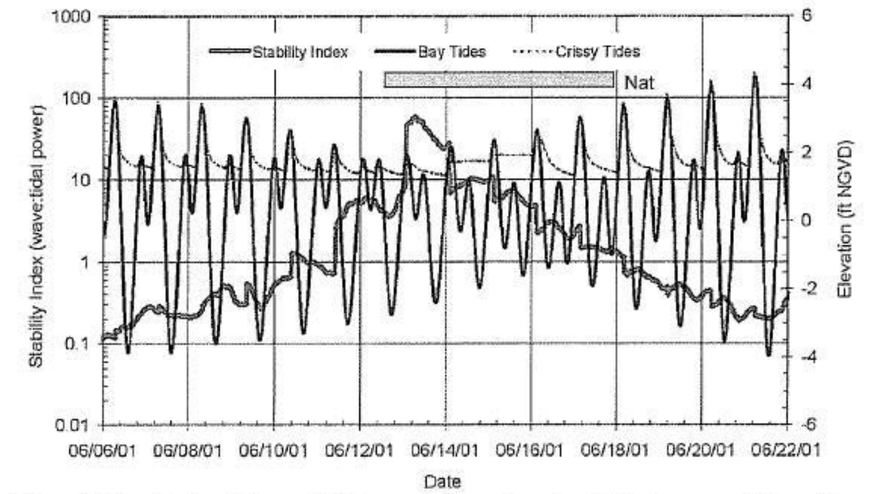
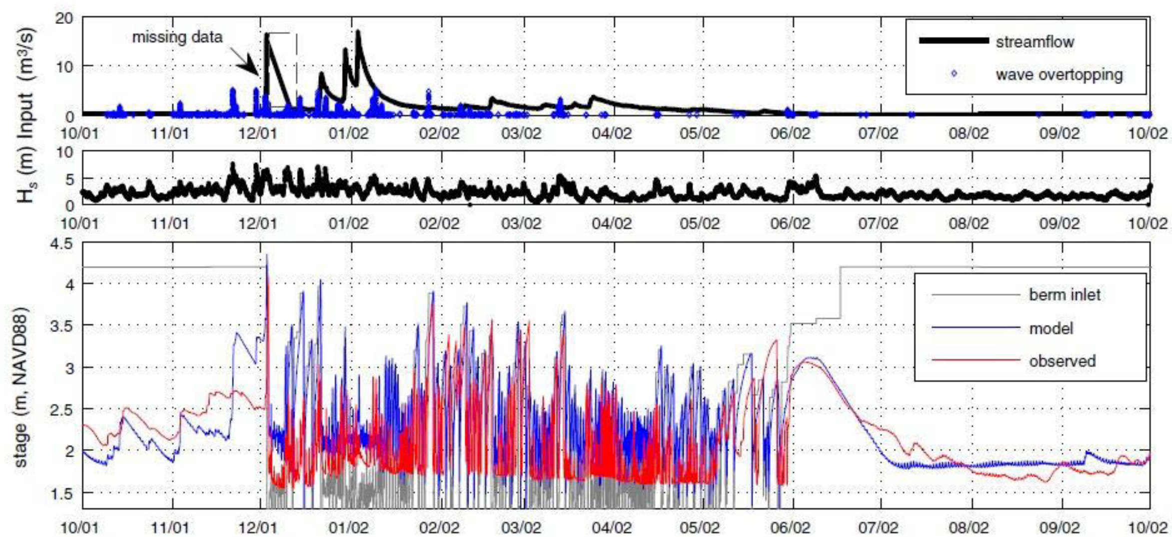


Figure 7. Monitoring data and QCM predictions showing inlet closure and breaching (June, 2001).

A. Rich, E.A. Keller / Geomorphology 191 (2013) 64–74



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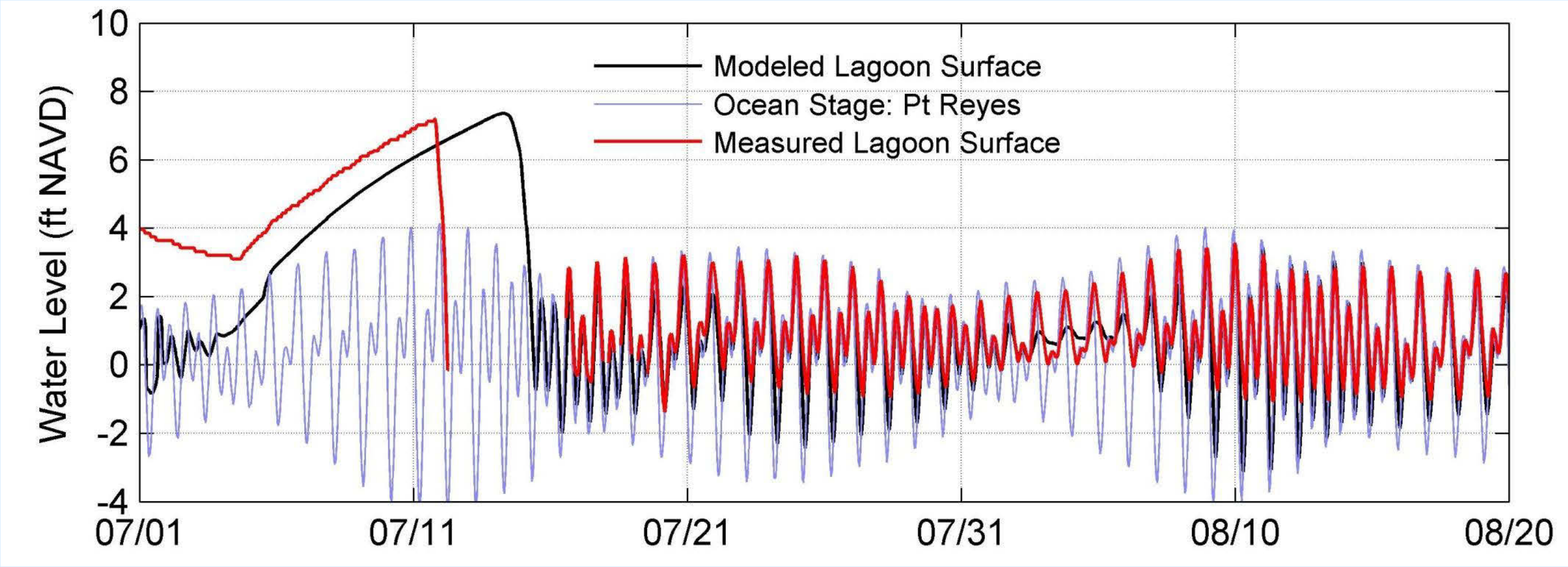
Model: *Russian River (Sonoma County)*

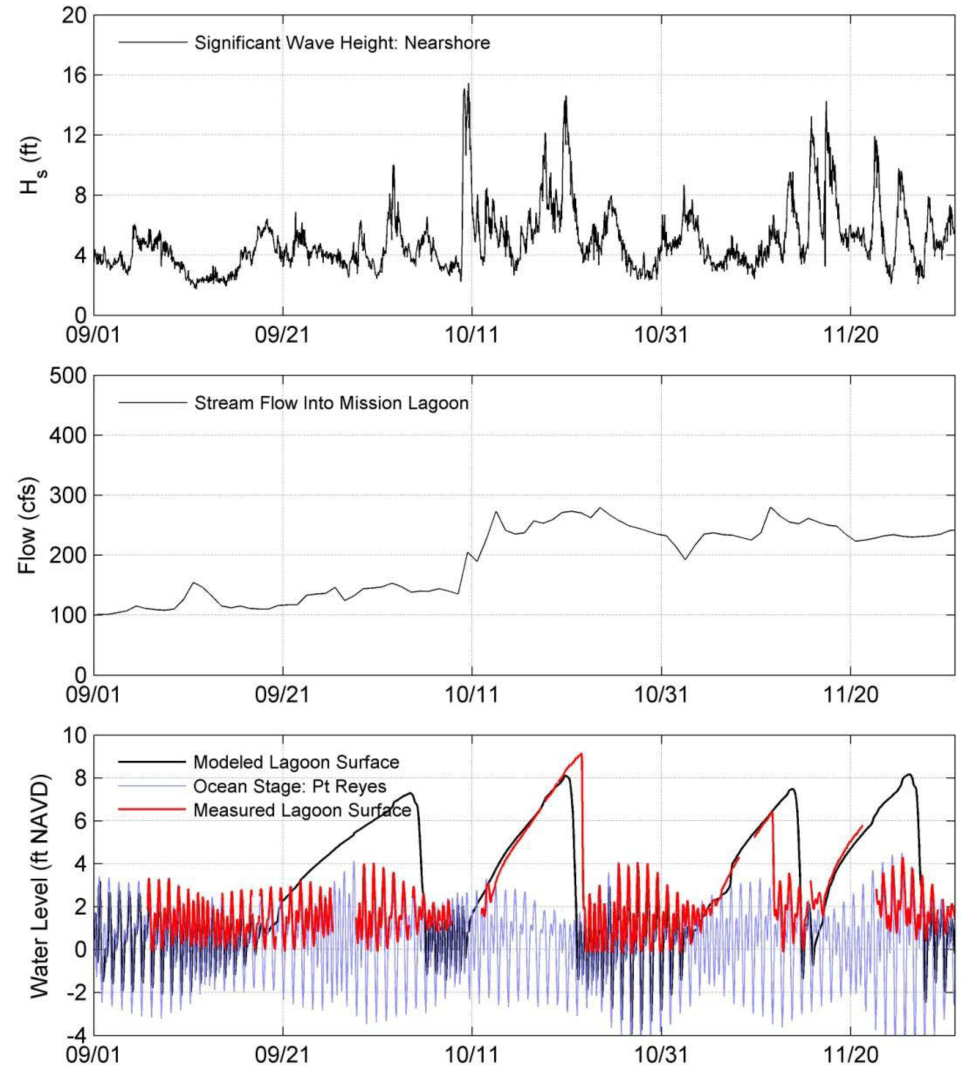
- **Large tidal prism (1600 Ac-ft)**
- **Annual floods: 10,000-100,000 cfs**
- **Closes 0-20 times per year**
- **Heavily managed (base flow maintained)**
- **Model run from 2001-2010**

Model: *Russian River (Sonoma County)*



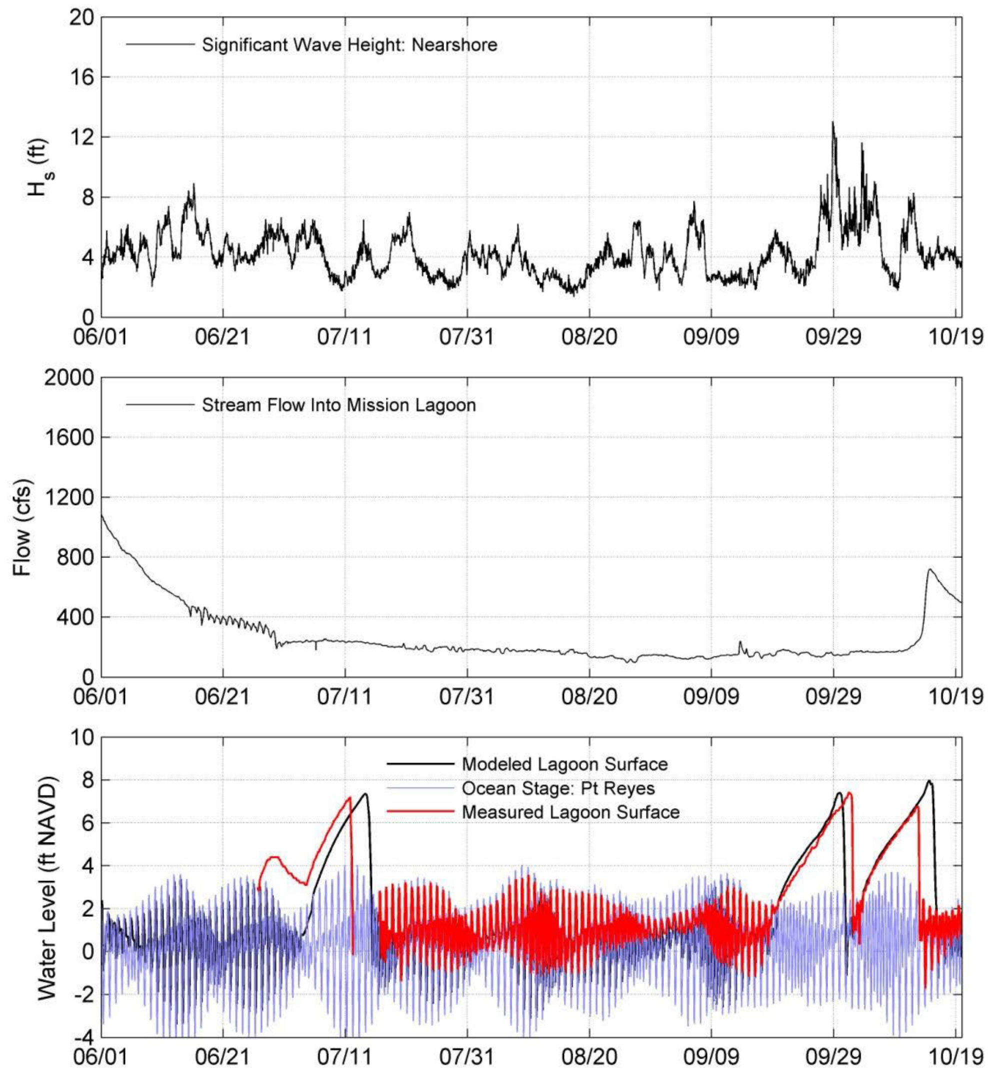
ESA PWA

Model: *Russian River (Sonoma County)*

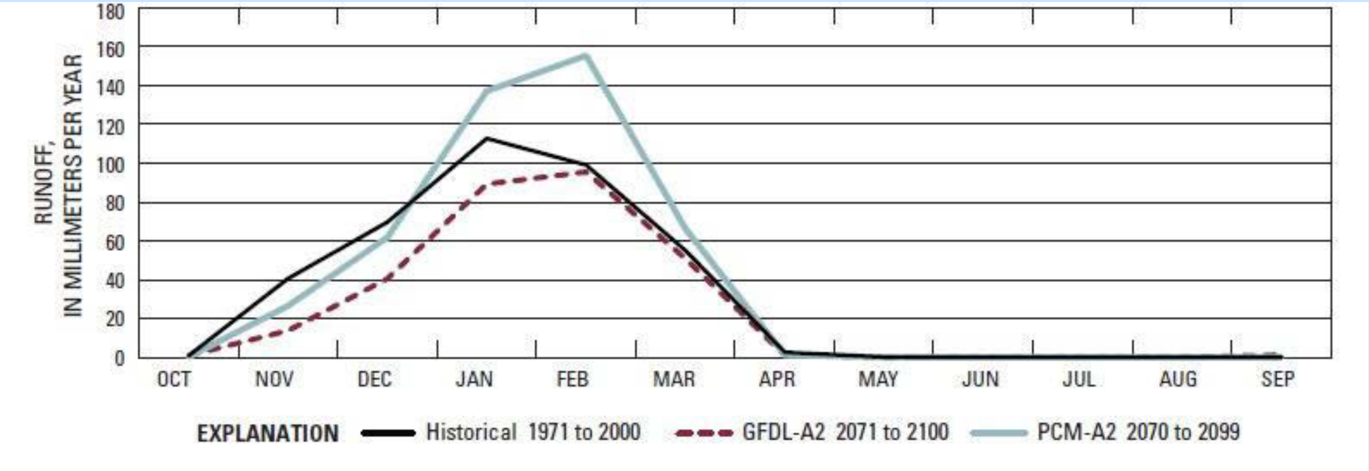


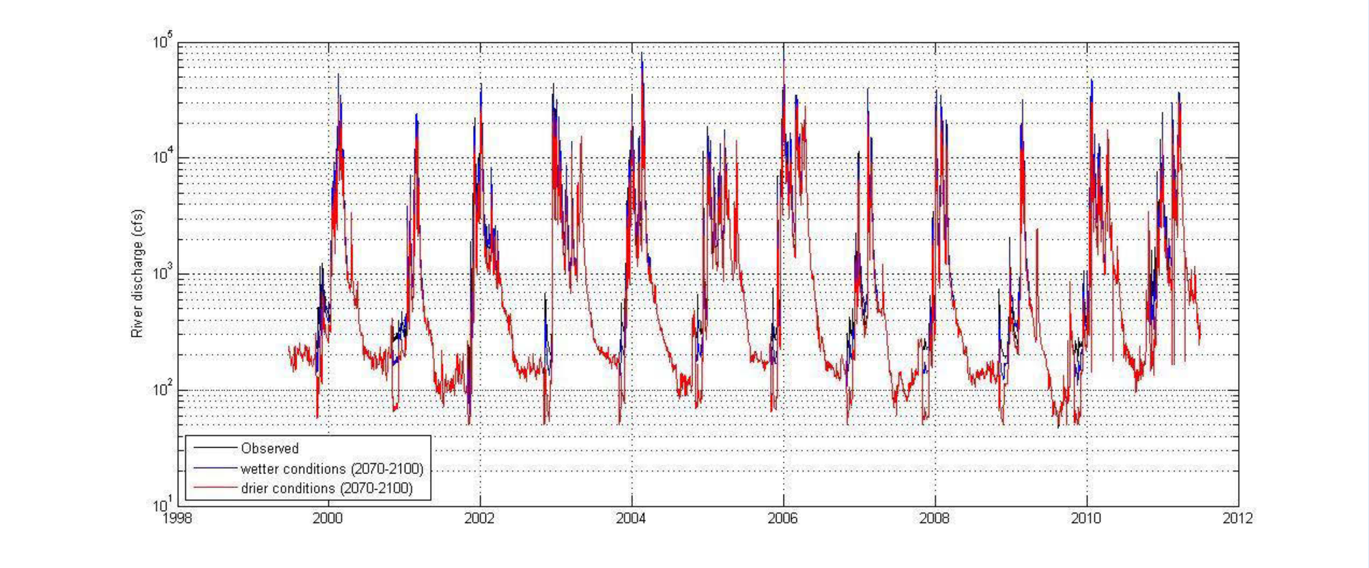
ESA PWA

Model: *Russian River (Sonoma County)*



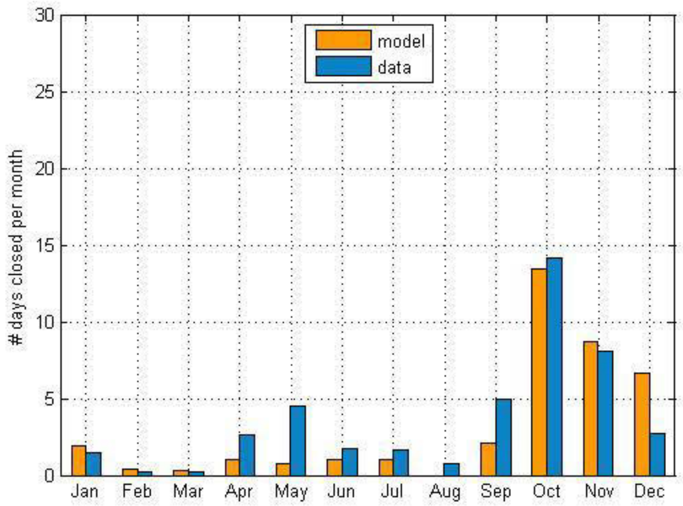
Model: *Russian River – Altered Inflows*



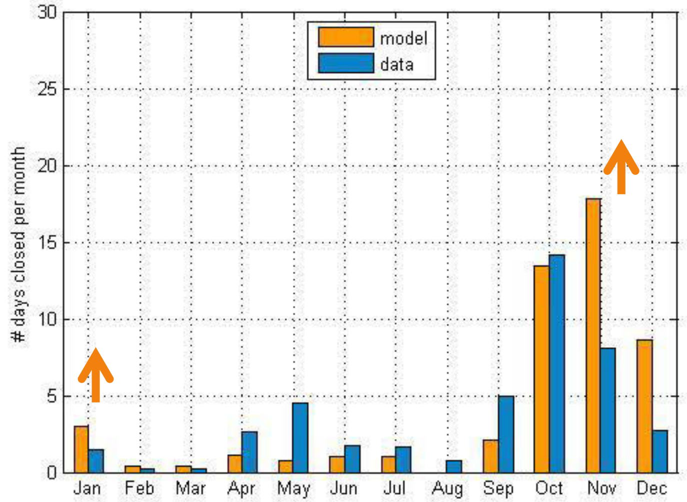


Model: *Russian River – Response to Change*

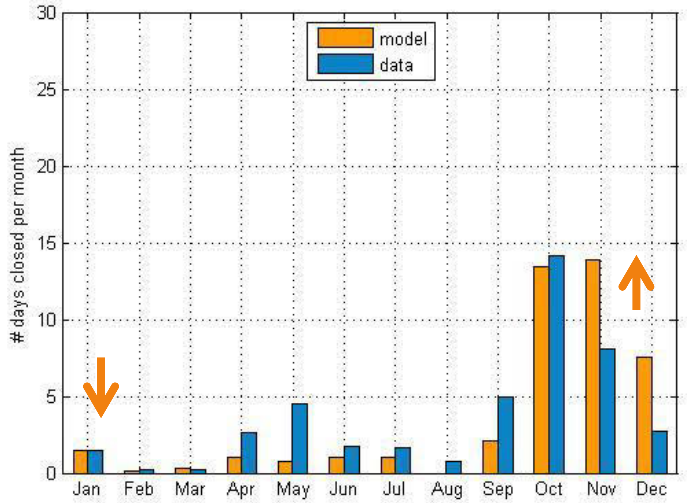
Observed Inflows



Drier conditions (2070-2100)



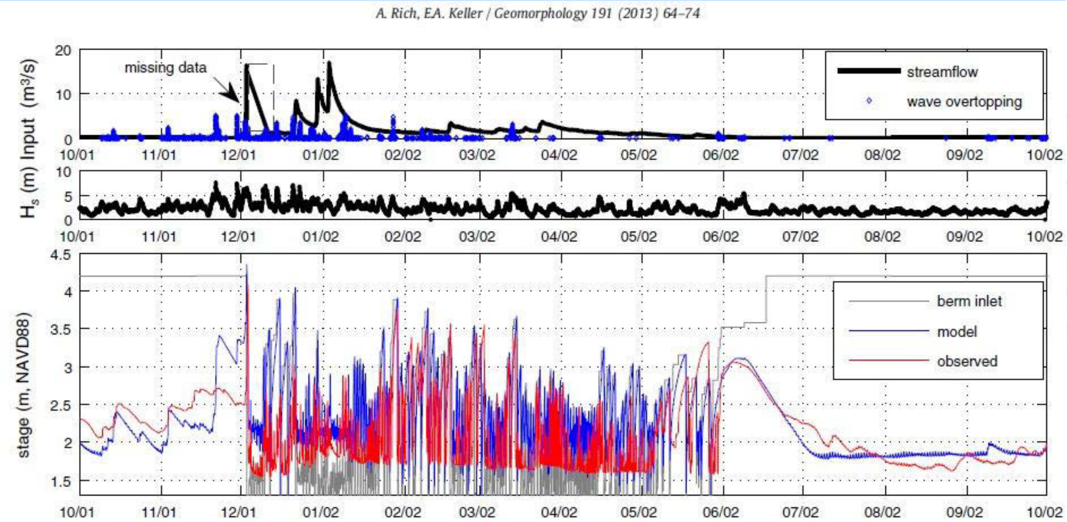
Wetter conditions (2070-2100)

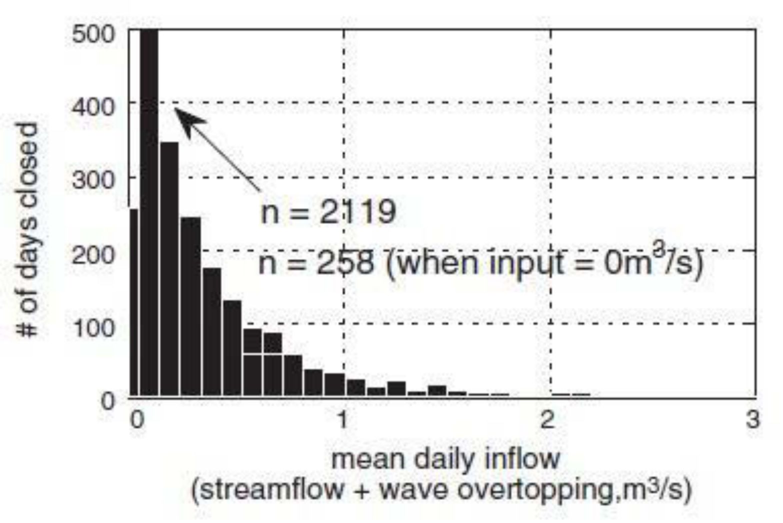


Either route leads to more inlet closure

Model: *Smaller lagoons*

- Small tidal prism (<50 Ac-ft)
- Peak floods: <10,000 cfs
- Closes seasonally
- Lagoon extremely sensitive to changes in freshwater flow





Rich and Keller (2013)

Summary

Potential impacts of shift in precipitation:

- Decrease in fall/spring runoff
- Prolonged summer dry conditions
- Increased variability of precipitation

Large lagoons (large tidal prism, less frequent closure)

- Inlet closure less sensitive to inflows (tidal prism dominates)
- Increased duration of closures
- Existing Impoundment/Management may mitigate this impact

Small lagoons (small tidal prism, seasonal closure)

•Longer, drier summers → longer duration of seasonal closures likely
•Increased variability in precip → more frequent closure/breaching?

Acknowledgements

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