Title
2D Hydrodynamic Modeling for Evaluating Restoration Potential of a Vernal Pool Complex

Author
Fryjoff-Hung, Anna Franciska

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2D Hydrodynamic Modeling for Evaluating Restoration Potential of a Vernal Pool Complex

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in

Environmental Systems

by

Anna Franciska Fryjoff-Hung

Committee in charge:

Professor Joshua H. Viers, Chair
Professor Mark C. Rains
Professor Teamrat A. Ghezzehei

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The Thesis of Anna Franciska Fryjoff-Hung is approved, and it is acceptable

in quality and form for publication on microfilm and electronically:

Mark C. Rains

Teamrat A. Ghezzehei

Joshua H. Viers, Chair

University of California, Merced

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Table of Contents

List of Figures

List of Tables

Anna Franciska Fryjoff-Hung
Environmental Systems
University of California, Merced, 2018
Advisor, Professor Joshua H. Viers

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Abstract

Vernal pool landscapes are rare and highly modified. The Merced Vernal Pools and Grassland Reserve consists of 6,500 protected acres, preserving sensitive vernal pool habitat and organisms. The Reserve contains a number of modified stock ponds that have caused extensive alteration of the historic landscape to capture and retain water for longer periods than the seasonal wetland complexes dispersed throughout the site. Using a combination of empirical data and 2D hydrodynamic modeling, our project seeks to better understand how water moves throughout the UC Merced Vernal Pools and Grassland Reserve in order to evaluate the feasibility of potential hydrological restoration activities and develop a better understanding of potential management strategies. This study aims to assess the feasibility of restoring or enhancing existing natural vernal pool complexes through increased inundation by reconnecting historical channels via small alterations in previously modified terrain.

A 2D hydrodynamic model was developed using HEC-RAS rain-on-grid methodology to assess the restorative potential of a vernal pool complex at Avocet Pond in the Merced Vernal Pools and Grassland Reserve. In this currently modified system, levees disconnect natural channels and reroute overland flows into the stock pond which behaves as a reservoir, removing water from downstream landscape processes. Increased inundation to natural habitats benefits native vernal pool species whose life histories are integrally tied to finite and variable hydroperiods. Invasive plant and animal species may be reduced through the reduction of perennial stock pond hydroperiods and increased inundation and hydrologic connectivity of wetland features. Base case hydroecological conditions were established as the formative basis for evaluating the benefit of various restoration scenarios. Proposed restoration scenarios implemented simple terrain modifications such as small breaks in conveyance levees or notching stock pond berms. Model simulations suggest that historical flow paths can be reconnected through minimal terrain alteration resulting in increased inundation to wetlands and other downstream environments and reduction of overall stock pond inflows and hydroperiod. Results of this study will serve as a demonstration of landscape scale restoration of a vernal pool grassland habitat that has been altered through past land uses so that similar restoration assessment methodology can be implemented on other preserved lands in the state.

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1. Introduction

Hydrologic connectivity is the water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle (Pringle, 2001). It is essential to the ecological integrity of landscapes and is often reduced or enhanced through human influence resulting in negative local and downstream environmental effects (Pringle, 2003). Human communities in areas of intra-annual seasonality and inter-annual predictability of freshwater supply have generally relied on intensive water management infrastructure to improve water supply reliability (Merenlender & Matella, 2013). Novel aquatic ecosystems that are easily exploited by alien species have emerged in arid and Mediterranean climate areas that exhibit high degrees of alteration to divert and provide water for other uses (Moyle, 2014). Pressure on water resources is increasing due to climate change, increased water extraction, and environmental flow requirements (Callow & Smettem, 2009). The struggle to manage water in California is exacerbated by growing urbanization, declining state and federal financial and technical support, shifting climate, and outdated infrastructure unable to support the capacity of growing demand. One of the historical failures of California's water management efforts is failure to adequately protect the environment. The implementation of hundreds of groundwater basins, 1,400 dams, and thousands of miles of canals, aqueducts, and levees to store and deliver water has led to large scale hydrologic disconnects and habitat loss, with 95% of the state's wetlands eliminated by the mid-1900s (Hanak et al., 2011).

Geographically Isolated Wetlands

Wetland ecosystems are being degraded and lost at a more rapid rate than that of other ecosystems (Millennium Ecosystem Assessment, 2005). Geographically isolated wetlands (GIW) are depressional landscape features surrounded by uplands that provide a wide range of ecological functions and ecosystem services through the exchange of materials, energy, and other organisms with other elements in hydrological and habitat networks, flow generation, nutrient and sediment retention, and biodiversity support (Cohen et al., 2016). Wetland protections initially established through the Clean Water Act were challenged in two Supreme Court decisions (2001 SWANCC, 2006 Rapanos) that limited the protections of GIWs to those with a "significant nexus" to navigable waters. Establishing a "significant nexus" is challenging due to the multiple pathways that GIWs can connect to surface water, resulting in the need for specific approaches and different types of models to understanding connectivity in different landscape settings (Golden et al., 2014). GIWs can be hydrologically connected to other wetlands and waterbodies via overland flow and surface runoff, groundwater, perched groundwater discharge, or horizontal near-surface flow (Golden et al., 2014), and more broadly through atmospheric fluxes of precipitation and evapotranspiration (Ali et al., 2017). However, due to lack of evidence of these connections to, and consequent effects on downstream waters, GIWs are frequently excluded from policy and management directives (Golden et al., 2017).

Modeling GIW Hydrologic Connectivity

GIW connectivity is the degree to which GIWs are linked to each other and to other landscape elements by surface, shallow subsurface, and deep groundwater flows operating across varying spatial and temporal scales (Golden et al., 2017). Multiple types of models have been used to model GIWs depending on the hydrologic component of interest. Watershed, groundwater, and coupled surface-subsurface flow models range in complexity and ability to answer specific questions about connectivity (Golden et al., 2014). Models generally fall into three groups based on the type of GIW connectivity information they provide: 1) spatially lumped models that have no spatial detail and supply implicit (estimated) connectivity information, 2) semi-distributed models that produce quasi-explicit connectivity information at a subbasin level, and 3) fully distributed models that yield explicit GIW connectivity at individual points within a watershed. Quantifying hydrologic connectivity of GIWs with models that verify measurements can assist decision making and help prioritize GIW protection and restoration by providing multiple lines of convergent scientific evidence (Golden et al., 2017). When modeling structural hydrologic connectivity of GIWs an accurate high resolution digital elevation model (DEM), spatial layer of wetland features for comparison, and hydrologic data are typically required as inputs. Model selection must consider cost, computational intensity, and data collection requirements, availability, and feasibility within the scope of the project

Defining and measuring hydrologic connectivity is approached, conceptualized, and implemented in research differently depending on the location, scale, and topic being investigated. Most research tends to focus on the structural rather than functional or process-based elements of hydrological connectivity, however both approaches emphasize the importance of the interaction between topographic controls and catchment processes as the key to understanding connectivity dynamics (Bracken et al., 2013). Topographic infrastructural terrain elements have been found to remove large proportions of upper catchments from hydrologic connections with the catchment outlet, reducing effective catchment area while increasing residence time in the basin where water is intercepted (Callow & Smettem, 2009). Meerkerk et al. (2009) has demonstrated that the removal and failure of infrastructural elements can lead to strong increases in hydrological connectivity and catchment discharge. Models have been developed to explore factors affecting the development of flow connections with changing topographic features, however few have been explicitly designed to enable hydrologic connectivity to develop as an emergent property in order to predict or explore changes in connectivity (Bracken et al., 2013).

Vernal Pools

Vernal pools are precipitation-filled seasonal wetlands inundated during periods when temperature is sufficient for plant growth, followed by a brief waterlogged-terrestrial stage and culminating in extreme desiccating soil conditions of extended duration (Keeley & Zedler, 1998). Vernal pools often occur together and with vernal swales as vernal pool systems with pools of varying sizes and shapes, floral and faunal composition, and hydroperiods. Length of inundation depends on the amount, timing, and duration of precipitation events throughout the season, as well as pool microtopography and landscape position, which affects both within and between year variability (Bauder, 2005). Due to the integrated hydrologic nature of vernal-pool landscapes, disturbance of upgradient vernal pools may have appreciable impacts on hydrological and biogeochemical processes in all downgradient vernal pools and streams (Rains, Dahlgren, Fogg, Harter, & Williamson, 2008). Vernal pool ecosystems are particularly vulnerable to conversion to agriculture, urbanization, or water storage, altered hydrology, inappropriate livestock grazing, and inadequate or inappropriate regulatory, management, and monitoring protocols (U.S. Fish and Wildlife Service, 2005).

Vernal Pool Formation and Hydrology

Vernal pool occurrence is correlated with particular landforms, geologic formations, and soil groups and series (Smith & Verrill, 1995). One of the major geologic controls of the physical and chemical hydrology of vernal pools is the underlying low permeability layers (claypans or hardpans) resulting in perched aquifers that connect uplands, vernal pools, and streams via surface or shallow subsurface flow (Rains, Fogg, Harter, Dahlgren, & Williamson, 2006). Significant differences in inundation can occur between subsets of vernal pools in series due to variability in the shallow, subsurface layer topography (Tham, 2018). Vernal pools occur in four stages that follow a seasonal sequence: 1) a wetting phase, where fall rains stimulate the germination of seeds and hatching, 2) an aquatic phase, when cumulative rainfall is sufficient to saturate soils and form pools, 3) a drying phase, when pool levels recede, and 4) a drought phase that occurs over the summer (Zedler, 1987). These phases contribute to both isolation and connectivity between uplands and other aquatic habitats. Vernal pools may be viewed as islands (R. F. Holland & Jain, 1981), however, clustered pools exhibit local exchange and ecological connectedness is implied by the global distribution of vernal pool adapted species (Zedler, 2003). Pools are also hydrologically connected during periods of saturation and serve as storage basins that are connected during times of maximum rainfall.

Vernal Pool Ecosystems

Vernal pools serve as ecological refuges and primary habitat for a number endemic specialists, many of which are adapted to these ephemeral ecosystems and are able to tolerate highly variable timing for the onset and duration of the growing season and endure long period of extreme dryness (Zedler, 2003). Vernal pool plant communities are floristically, topographically, and geographically autonomous, and are one of the few low-elevation habitats in California that are dominated by native plant species (Barbour et al., 2007). Water accumulation in vernal pools acts as an ecological filter for non-native plant establishment, while native plants are adapted to the natural ponding stages of the pools, exhibiting increased frequency with early season precipitation which promotes the onset on inundation (Javornik & Collinge, 2016). Pools dominated by native plants tend to have longer inundation durations than invasive-dominated pools, which can reduce pond depth and cause positive feedback recruitment of additional non-native species through accumulated litter deposition (Faist & Beals, 2018). Brachiopod crustaceans exhibit high diversity and endemism over a large scale due to the patchy nature of pool distribution and variety of physical and chemical conditions present within pools. High diversity and co-occurrence within pools is related to inundation duration, developmental time, niche overlap, pool size, and habitat heterogeneity (Simovich, 1998). It is estimated 15-30% of crustacean species in Central Valley vernal pools may have already gone extinct due to habitat loss (King, 1998). California tiger salamander (*Ambystoma californiense*) (CTS) utilize vernal pools for breeding and larval development, spending their adult stages in upland rodent burrows. Larval development is constrained by pool hydroperiod (Trenham, Shaffer, Koenig, & Stromberg, 2000). They historically probably relied on vernal pools for breeding habitat, but now make extensive use of stock ponds constructed for cattle (Lannoo, 2005), some of which persist as perennial features on the landscape. Increased pond durations have been found to increase the impact of predators (Schneider & Frost, 1996). These modified breeding habitats and introduction of congeners capable of interbreeding have threatened CTS (Riley et al., 2003) which serve as top predators in seasonal pond systems. Livestock grazing plays an important role in maintaining species diversity in vernal pool grasslands through selective foraging of exotic grasses which can reduce pool hydroperiod through increased evapotranspiration negatively affecting community diversity of native species (Marty, 2005, 2015) . The endemic nature of the flora and fauna combined with significant habitat loss and increased invasion have brought attention to the conservation and restoration of vernal pools in the recent decades (Barbour et al., 2007).

It is estimated that 60-85% of vernal pool habitat in the Central Valley has been lost over the past two centuries (R. Holland, 1978). Eastern Merced County contains the most diverse and abundant vernal pools of any region in California approximately 6,300 of which were protected by the designation of the Merced Vernal Pools and Grassland Reserve in 2014 (Swarth et al., 2017). The management requirements for this land are intended to maintain and enhance values for endangered and other sensitive species and the ecosystems that support them (Airola, 2008). Species dependent on the vernal pool ecosystem known to occur on the conservation lands include Succulent owl's-clover (*Castilleja campestris ssp. succulenta*), Colusa grass (*Neostapfia colusana*), San Joaquin Valley orcutt grass (*Orcuttia inaequalis*), Conservancy fairy shrimp (*Branchinecta conservatio*), Vernal pool fairy shrimp (*Branchinecta lynchi*), Midvalley fairy shrimp (*Branchinecta mesovallensis*), Vernal pool tadpole shrimp (*Lepidurus packardi*), and California tiger salamander (*Ambystoma californiense*) (Airola, 2008).

Modeling Vernal Pools

Limited explicit hydrodynamic models have been applied directly to vernal pool ecosystems. Modeling attempts are primarily focused on simulating and predicting hydroperiods to inform management, modification, and construction of pools (Garmendia & Pedrola-Monfort, 2010; Pyke, 2004) as well as future impacts of climate change (Pyke, 2005). These models are generally based on simplified assumptions of pond filling dynamics and limited to individual or small sets of pools. Hydraulic models can provide predictions of resulting hydrology of proposed restoration plans (Marois & Mitsch, 2017). 1D, 1D/2D, 2D, and 3D hydrodynamic models have been applied to other types of wetlands for restoration purposes (Marsooli, Orton, Georgas, & Blumberg, 2016; Wang, Li, Li, & Hu, 2014; Wen et al., 2013). However, most of these models have predictable or gaged inflow data, which is not consistent with the variable hydrologic regime of vernal pool ecosystems.

Vernal Pool Conservation

Compensatory mitigation is required to replace the loss of wetlands authorized through Section 404 of the Clean Water Act and serves as a tool in achieving the goal of "no net loss" of wetland acreage and function (Environmental Protection Agency, 2008). Methods of compensatory mitigation include restoration, establishment (creation), enhancement, and preservation and may be accomplished through permittee-responsible compensatory mitigation, mitigation banks, and in-lieu fee mitigation. As the majority of vernal pool habitat has been destroyed or altered, a typical mitigation strategy is pool creation. Creation involves building new pools as opposed to restoration which attempts to return an altered pool to a preexisting condition. Constructed pools often fail to reproduce adequate pool hydroperiods (Calhoun, Arrigoni, Brooks, Hunter, & Richter, 2014; De Weese, 1996) and performance standards are vague and inconsistently applied when implementing restoration projects (Schlatter, Faist, & Collinge, 2016).

Research Objectives

This study is part of a larger project, the overall objective of which is to develop a restoration feasibility plan to increase the amount of suitable habitat for native and/or listed vernal pool and grassland plant and wildlife species found on the Merced Vernal Pool and Grassland Reserve at the University of California, Merced campus (Reserve herein). The potential restoration of vernal pools and landscape hydrologic connectivity would enhance the Reserve for numerous listed and other special-status species and improve overall ecosystem functions. Additionally, these restoration activities would be consistent the mission of the UC Natural Reserve System to maintain representative examples of key California habitat types, providing undisturbed environments for research, education, and public service to contribute to the understanding and stewardship of the earth (UCNRS, 2006).

The specific aim of this study is to investigate the effects of small scale terrain alterations on the structural hydrologic connectivity in a vernal pool complex using a combination of empirical data and 2D hydrodynamic modeling. In this currently modified system the stock ponds behave as reservoirs, which may benefit vernal pool dependent species in dry years, but overall do not provide the habitat benefit and remove water from downstream landscape processes. This study aims to assess the feasibility of restoring or enhancing existing natural vernal pool complexes through increased inundation by reconnecting historical channels via small alterations in previously modified terrain using HEC-RAS 2D hydrodynamic rain-on-grid modeling. Results of this study will serve as a demonstration of landscape scale restoration of a vernal pool grassland habitat that has been altered through past land uses so that similar restoration assessment methodology can be implemented on other preserved lands in the state.

2. Methods

The primary objective of this study is the development of a geospatial hydrodynamic model that represents catchment-scale hydrological conditions and alteration, such that future restoration scenarios can be evaluated. Integrating measurements and models can improve and facilitate the understanding of the connectivity of GIWs within the Reserve at a range of spatial and temporal scales. Restoring hydrologic function may only require minor adjustments (notching) to existing infrastructure rather than complete removal and restoration of a complete heterogeneous topographic landscape. Complete removal of berms and levees may also result in loss of currently occupied habitat by sensitive species.

Using a combination of empirical data and high resolution geospatial modeling, base case hydroecological conditions were established within the model domain which set the formative basis for evaluating the benefit of different restoration scenarios. Our present focus is in developing and delineating catchment level hydroecological processes in and around Avocet Pond on the Reserve and assess to what degree the terrain can be reconfigured to meet the habitat needs of threatened/endangered species in human altered environments while providing more water for downstream processes.

Site Description

Eastern Merced County

The study was conducted in Eastern Merced County within the broader Central Valley of California. The climate is Mediterranean with cool, wet winters and hot, dry summers which provides the annual rainfall patterns essential for the development of vernal pools and other ephemeral wetlands. Rainfall varies interannually and spatially across the region with annual averages ranging 230-380 mm depending on elevation and 90% of the precipitation occurring between November to April. The western and eastern boundaries of the region delimit a distinct topographic and biogeographic unit of undulating terrain topography from above the historic San Joaquin River floodplain to the base of the Sierra Nevada foothills. This area supports the largest block of unfragmented vernal pool habitat remaining in California. Low slope basins with undulating mima mound topography typically support a high density of vernal pools, however most mima mound topography and associated pools historically present in California have been eliminated by agricultural and urban development. A variety of natural (rivers, creeks, lakes, and swales) and human made surface waters (irrigation canals, reservoirs, and stockponds) convey, store, and redistribute hydrologic flows between vernal pools into ephemeral drainages that ultimately flow out of the region (Vollmar, 2002).

Merced Vernal Pools and Grassland Reserve

The Merced Vernal Pools and Grassland Reserve (Figure 1) consists of 6,500 protected acres preserving sensitive vernal pool habitat and organisms, containing an estimated 6,202 typical vernal pools, 32 large vernal pools, 7 playa pools, 84 swale wetlands, and mima mound topography. The Reserve was historically and is still currently used for livestock grazing and contains a number of seasonal and perennial stock ponds that capture and retain water for longer periods than the seasonal wetlands and vernal pool complexes dispersed throughout the site. Other landscape alterations including fences, dirt roads, berms, and other water source development have occurred over the years are part of the ranching operations. Initial road and stock pond development likely occurred between 1918-1948 (University of California, 2018). Historically, vernal pools and swales were present in many of the areas that were modified, these developments also altered the upland topography and general watershed conditions within the Reserve.

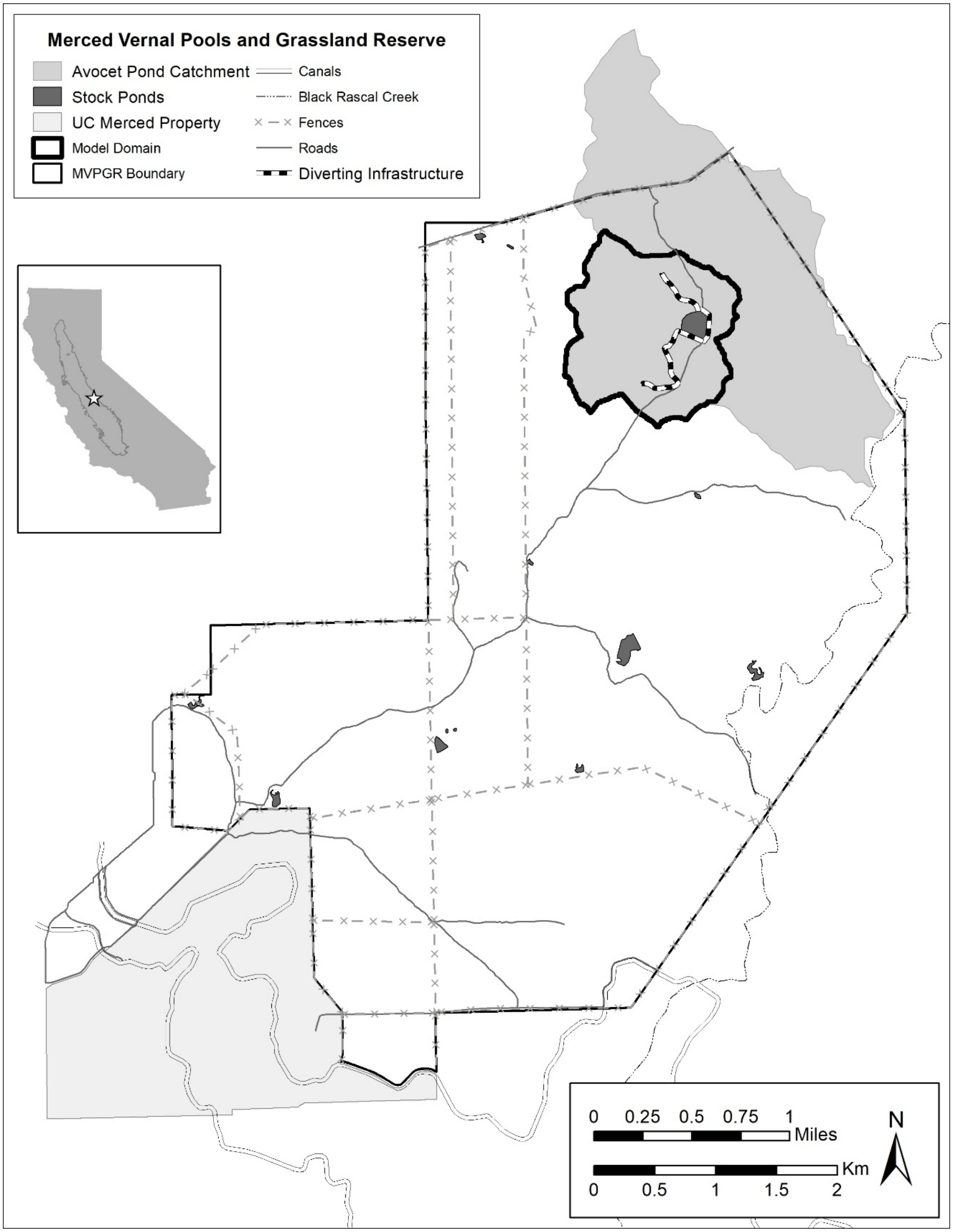

Figure 1 Merced Vernal Pools and Grassland Reserve Overview showing stock ponds and study site catchments

Study Site: Avocet Pond

Avocet Pond, a large stock pond located in the northeast corner of the Reserve, served as the primary site for data collection and modeling. The site is situated in a low topographic saddle and is highly modified, bounded on three sides by raised berms and roadways with two conveyance levees extending across the natural wetland landscape artificially diverting flow from two headwater catchments into the pond. The site infrastructure reduces the effective catchment area draining into Black Rascal Creek, a seasonal creek that flows along the southern border of the Reserve, diverting ~175 acres or ~13% of greater 1300-acre catchment into the pond. Diverting infrastructure remains in the third headwater catchment, but the features are not continuous and although water is initially diverted into a small side stock pond, surface flows continue downstream through breaks in the levees. There are two breaks in the Lower Levee, resulting in loss of historical diversion capacity and function. There are two inflows (Upper and Lower) that drain along the conveyance levees into the pond and one outflow that releases water back into the downstream catchment when the pond is at or above capacity. The inflow channels are downcutting through the underlying hardpan at the inflows, while headcutting and exposure of hardpan exists at other modified locations around the study site.

At capacity the pond covers approximately 10.4 acres and holds ~65 acre-ft of water (Figure 2). Average depth is 1.47 m with a maximum depth of ~2.61 m. The modifications divert approximately 175 acres into the pond which functions as a small reservoir and restricts natural inundation of the hydrologically disconnected wetlands downstream of the diversions. Persistent water in dry years may benefit vernal pool dependent species but diversion and retention likely shorten inundation periods downstream, reducing overall habitat.

The pond is located in Grazing Unit 3 of the Reserve, which comprises approximately 50% (3,327 acres) of the total Reserve area and includes multiple water sources for grazing, including four other stock ponds, Black Rascal Creek, and vernal and playa pools when inundated. Recent historical imagery indicates that the pond remains a perennial water source in an ephemeral wetland landscape most years. Sensitive species surveyed in and around the study site are Colusa grass (*Neostapfia colusana*), Vernal pool fairy shrimp (*Branchinecta lynchi*), and California tiger salamander (*Ambystoma californiense*) (LSA, 2018).

Avocet Pond provides a good opportunity to study hydrologic restoration potential as this single pond has a large impact. Due to the intensive data collection required to model this complex system, initial model methodology was developed at this site while additional data were collected at other stock ponds within the Reserve for future model application.

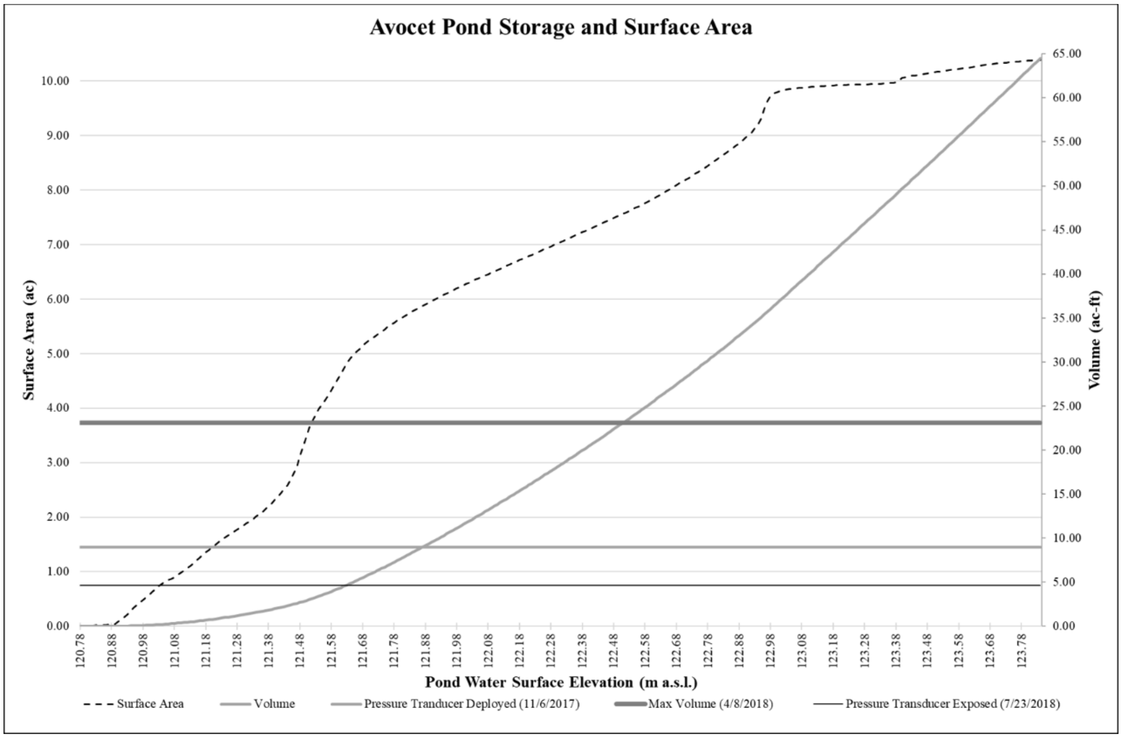

Figure 2 Avocet Pond Storage and Surface Area with PT deployment, exposure, and maximum volumes for the 2018 field season

Identifying Model Domains and Aerial Survey Extents

Prior to field data collection, a number of analyses were conducted in ArcGIS to identify targeted areas for aerial surveys. Initial modeling was conducted using a freely available 10m digital elevation model (DEM) from the USGS and heads up digitization of diverting infrastructure visible in aerial imagery. A depressionless DEM was generated through an iterative process using a suite of tools in the ArcGIS Hydrology toolset to identify and fill sinks present in the DEM. Once a depressionless DEM was created flow direction and flowline accumulation (streamlines) were defined across the landscape, and upstream catchments were delineated based on key intersection points of flowlines with diverting infrastructure and terminal reaches at Black Rascal Creek. Streamline diversion points were identified at the intersection of the flow accumulation raster (streamlines) and digitized levee features and pour points were created for upstream catchment generation. Catchments were generated for any streamline diverted by infrastructure into Avocet Pond as well as the larger networks fed by these reaches terminating in Black Rascal Creek.

The watershed generated from the headwaters to their terminus with Black Rascal Creek was used to define the bounding coordinates for photogrammetric aerial surveys and may serve as an extended future modeling domain. A subwatershed generated upstream from the major streamlines diverted into Avocet Pond will serve as the initial modeling domain (Figure 3). This subwatershed consists of six subbasins, three headwater subbasins (Upper, Lower, Side) above the diversion infrastructure and corresponding similar sized subbasins below the diversions. Subbasins below the Upper and Lower Diversions were treated as floodplains. Elevation within the model domain ranged from 114m to 180m with steep headwater slopes rapidly leveling off into the low gradient floodplains. The subbasins below the diversions were comprised of 15.6% wetlands on average, while the headwater subbasins were comprised of 4.5% wetlands on average. The Upper Floodplain contained 9.39 acres of delineated wetland features and the Lower Floodplain contained 6.61 acres of delineated wetland features.

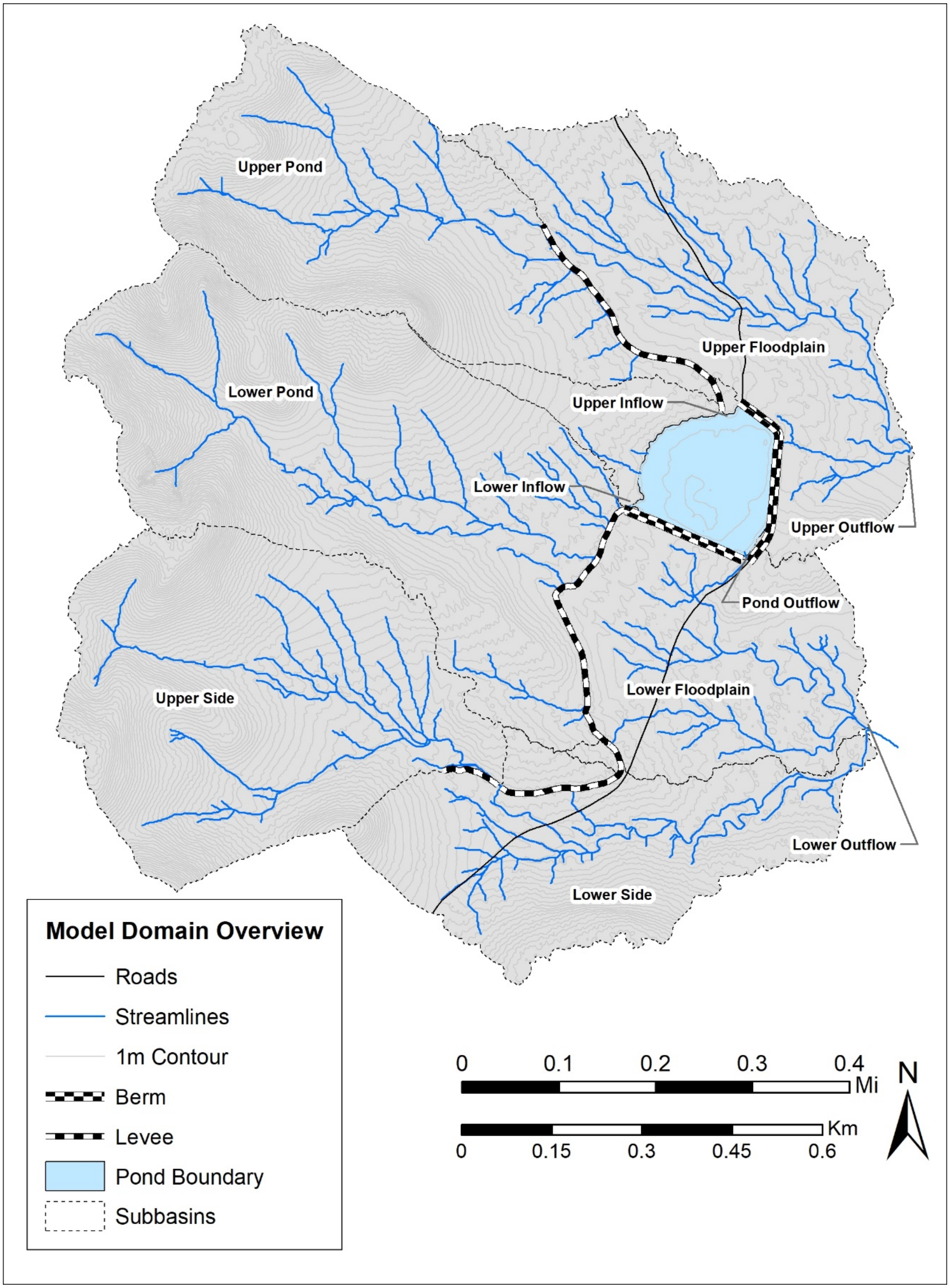

Figure 3 Model Domain Overview including site modifications and subbasins

Field Methods

Field work was continuously conducted at the study site and across the Reserve from mid-February 2017 through mid-August 2018. Stock ponds were instrumented with pressure transducers in order to gage changes in water surface elevation (WSE) during precipitation filling events and estimate drawdown rates. This information was used for hydrodynamic model calibration and as inputs for target hydroperiod estimation for CTS. A high resolution digital elevation model was collected through structure from motion photogrammetry for use and modification as the current and restoration terrain layer within the model. Site conditions were monitored throughout the seasons for instrument and model validation. Hydrodynamic modeling was conducted in HEC-RAS using 2D Direct Rain-on-Grid methodology. The two storms that contributed the most volume to the pond during the 2018 water year were modeled under current conditions and restoration scenarios in order to assess inundation extents and restorative acreage potential.

GPS Surveys

TopCon GRS-1 handheld and Hiper V sub-meter accuracy GPS units (TopCon, Livermore, California, USA) were utilized during the course of this study. Elevational benchmarks for the Real-time kinematic (RTK) GPS/GNSS surveys were established at Avocet Pond and outside the Reserve on La Paloma Road for use when cattle were in the pasture. The GRS-1 handheld devices were used to collect pond boundaries throughout the season to estimate pond WSE and surface area and validate instrument data. The RTK was used to precisely record instrument and transect locations, ground control points for DEM georegistration, diversion feature geometry and slope breaks, as well as validate elevations from the photogrammetrically derived DEM. A 150 m gridded RTK survey was conducted during the Fall of 2017 across all accessible areas within the larger watershed. A 30 m gridded RTK survey was conducted across the pond bed and surrounding upload during the Fall of 2018 after complete drawdown.

Unmanned Aerial Vehicle Surveys

Aerial surveys were conducted using unmanned aerial vehicles (UAVs) to collect structure from motion (SfM) digital elevation models, multispectral imagery, and seasonal observations of general site characteristics and inundation between modeled storm events. A fine scale corrected DEM was needed to accurately characterize hydrologic connectivity within the low gradient, topographically complex catchments. The SfM DEM was collected using a 3DR Solo quadcopter UAV outfitted with a GoPro Hero 4. Mission transects were generated prior to going into the field using Mission Planner software. UAV collected imagery was processed using the photogrammetry software Pix4D. The processed DEM had a resolution of 6 cm and was rescaled to 0.5 m for use as the terrain within the hydrodynamic model. Rescaling occurred in order to reduce model computation time. Vertical accuracy of the merged model terrain was ±0.39 m for the full watershed, ± 0.35 m within the model domain, ±0.18 m along levee and berm slope breaks, and ±0.14 m within the merged pond bathymetry and SfM DEM uplands.

Bathymetric Surveys

Many of the stock ponds on the Reserve remain inundated year-round, therefore a continuous terrain dataset of the landscape cannot be derived solely from photogrammetry. Bathymetry data were collected during the Spring 2017 field season using a SensePlatypus Lutra Prop autonomous robotic watercraft outfitted with a Lowrance HDS-7 sonar. Surveys were conducted along 15 m gridded transects. The high-water line of the pond was collected with a handheld GPS unit at the time of the sonar data collection in order to estimate WSE as a source of surface interpolation in areas too shallow for bathymetric surveys. Sonar data were processed using Lowrance Sonar Viewer software, outputting a csv with multiple soundings per unique coordinate. Average water depths were calculated for each location in R and adjusted for sensor depth (Holmes, Nichols, & Viers, 2014). Using ArcMap 10.5, the points were interpolated into a raster surface using kriging resulting in a 0.5 m digital elevation model of the pond bottom. The digital elevation model and bathymetry were combined into a single dataset using the Spatial Analyst Supplemental Toolbox for ArcGIS to be used and modified as the modeling terrain in HEC-RAS.

Hydrologic Data

The primary hydrologic data used in this study were from the seasonal water logger measurements taken in Avocet Pond. Two Onset HOBO U20 Water Level Data Loggers were deployed at the study site, one in the pond the measure hydrologic flux and the other terrestrially for barometric pressure compensation. Data were collected at 15-minute intervals during instrument deployment from November 6, 2017 to August 10, 2018. Pond depth was converted to WSE by adding instrument depth to the elevation (m a.s.l.) at which the pressure transducer was located, based on the fused DEM and bathymetry terrain. Pond WSE values pre and post-modeled storm events were used as volume checks for model calibration. Precipitation data were acquired from the UC Merced CDEC weather station (Appendix I) operated by the Merced Irrigation District located at the western edge of the Reserve and used as the input boundary condition in the model (Figure 4-5).

Game Camera Seasonal Timelapse Imagery

Moultrie M-999i game cameras were deployed from December 15, 2017-August 10, 2018. Cameras were installed at the pond inflows positioned to capture images of the pond bed and inflow channels every 15 minutes during daylight hours. Images were compiled into timelapse videos for different types of visual site assessment including grazing visitation and channel inundation during storm surges.

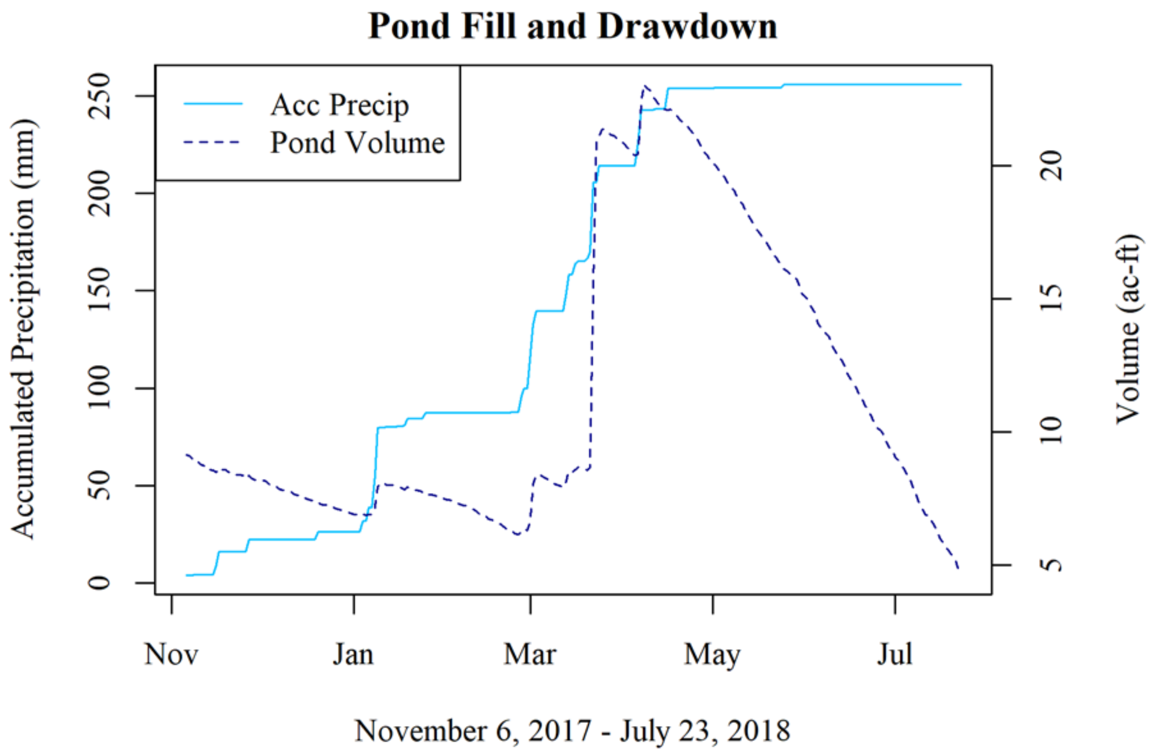

Figure 4 Field Season Accumulated Precipitation vs. Pond Volume

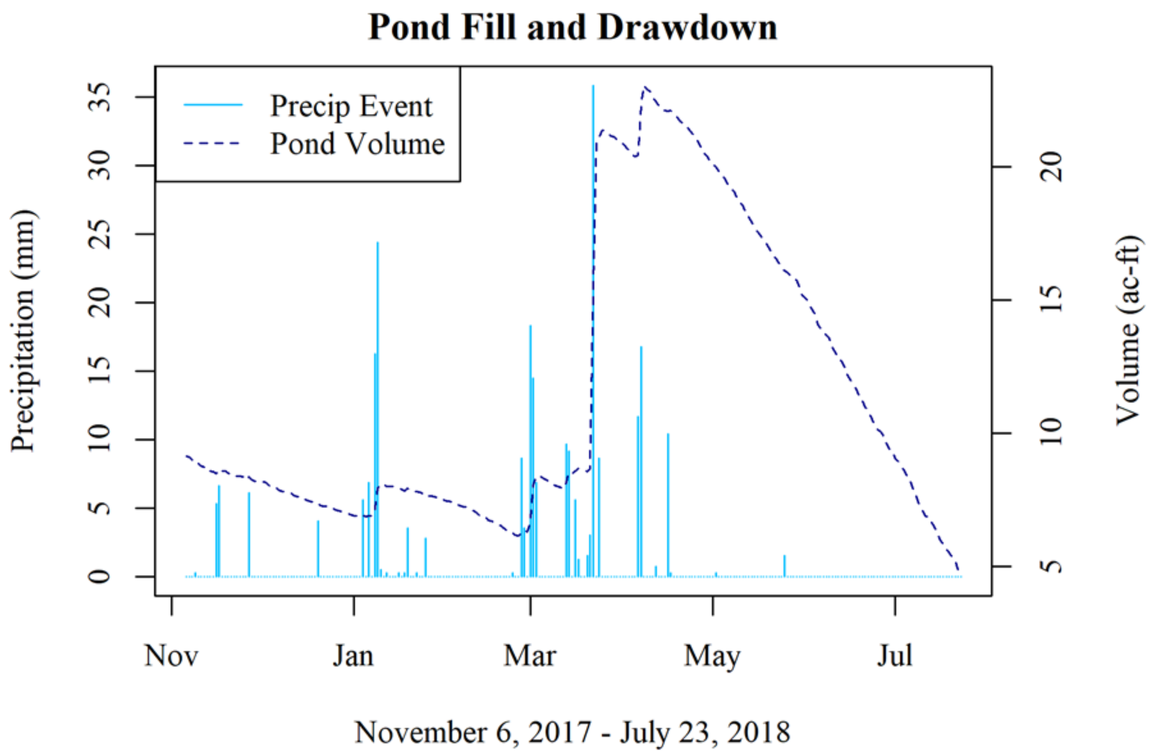

Figure 5 Field Season Precipitation Events vs. Pond Volume

Modeling

Hydrodynamic Modeling

A two-dimensional hydrodynamic model was developed for the subbasins immediately above and below the conveyance berms constructed to divert runoff from the surrounding watershed into Avocet Pond. The modeling used the U.S Army Corp of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS 5.0.5) software (G. W. Brunner, 2016). HEC-RAS is freely available (Appendix I) allowing users to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling. Due to the ungaged, intermittent flows in the system and inability of the 1D model to handle dry conditions, the entire study area was modeled in the 2D domain with direct rainfall as the sole hydrologic input. The HEC-RAS 2D flow modeling algorithm computes detailed hydraulic properties for 2D computational cells and cell faces based on the underlying terrain. These subgrid capabilities allow the model to use larger computational cells, without losing much of the detail of the underlying terrain that govern the movement of the flow (Casulli, 2008). The 2D unsteady flow equations uses an Implicit Finite Volume algorithm, which allows for larger computational timesteps, improved stability, and more efficient wetting and drying of 2D cells. The software is able to use both structured and unstructured meshes, meaning that computational cells can range from three to eight-sided elements or varying sizes.

The model uses topographic, hydrologic, and spatially variable land surface roughness as inputs. Using the hydrologic flux data collected in the pond and precipitation data from the UCM CDEC weather station located on the Reserve (Appendix II), the current extent of floodplain inundation was modeled for the two storms season that contributed the largest inflow volumes to the pond during the 2018 Water Year. Once the models were calibrated to current pre-restoration topographic conditions, computed rainfall losses were modeled over the post-restoration topographic scenarios. Changes in inflow volume to the pond and changing extents in downstream inundation were calculated and compared for each restoration scenario.

2D Direct Rain-on-Grid

2D modeling is advantageous in areas where flow is expected to spread, bifurcating flow paths, wide floodplains, wetland studies, lake or estuary studies, and alluvial fans (G. Brunner, 2015). Recent and continued advancements in computing power make this type of modeling an invaluable tool for planning and design. With regard to stream restoration and wetland creation it is necessary to understand how flow spreads over broad, flat landscapes with minor changes in topography and slope. Using 2D models, results are delineated down to the 2D cell resolution, unlike lump sum or semi-distributed catchment models which summarize values at specified point locations within a watershed. Due to the intermittent and disconnected hydrologic flows, unknown and variable antecedent soil moisture conditions, and variable subsurface topography it was difficult to apply traditional 1D or coupled 1D/2D models to a vernal pool landscape. Direct Rain-on-Grid methodology was chosen to model specific storm events that occurred during the field season. This methodology is relatively new to the hydraulic modeling industry and utilizes high resolution topography and roughness values to route hydrologic flows applied as precipitation to 2D cells. Low data requirements and high accuracy make this type of modeling advantageous, however limited guidance is available for calibration and validation; common sense and judgement must be used when interpreting results. HEC-RAS currently does not incorporate infiltration or evapotranspiration; therefore, rainfall losses must be calculated using a separate rainfall-runoff model such as HEC-HMS, with the resulting rainfall excess applied in the 2D model. Due to lack of data adequate for accurate rainfall-runoff modeling the stock pond WSE before and after modeled storm events was used as a volume check to calibrate the model and estimate appropriate precipitation application.

Model Geometry

The grid representing the model domain consisted of 143,076 computational grid cells ranging in size from 0.7-7 m depending on topographic location within the model domain. Breaklines were placed along levees and select streams to enforce mesh generation to align computational cell faces along hydraulically significant topographic features. The pond and floodplain subbasins were refined to higher resolution cells than the upstream subbasins in order to gain high accuracy outputs in areas of restoration potential. Output was generated at the 0.5 m resolution of the topographic input provided by the subgrid capability of the model. The total area of the model domain was ~1.6 km^2.

Model Timestep Selection

Model computational timestep was estimated using the Courant condition and run using the Diffusion Wave equation set. The Courant number controls the number of grid cells that water will travel between computations. For 2D models a maximum Courant number of 1 is recommended in order to get a more accurate and stable wetting front when starting with completely dry cells (G. Brunner, 2015). Computational timesteps based on the Courant number varied between 7.5 sec - 2 min, allowing the model to iterate and adjust the minimum or maximum Courant number and provide a stable numerical solution (G. Brunner, 2016).

Solution Convergence

Model solution convergence was achieved by testing the consistency of the computational mesh and selected time step simultaneously. The computational grid was initially set to 10 m and then refined to ensure that key topographic features controlling flow were represented. Breaklines were initially inserted on the tops of levees and berms, pond inflow channels, and through current levee breaks. Additional breaklines were added to the model to drain artificially ponded areas in the upper subcatchment streams that were constrained by the structured alignment of the coarse resolution mesh. Upper subcatchment areas were left at a coarser resolution due to the fact that the landscape alteration won’t affect the upstream hydrology.

Restoration Scenarios

Restoring hydrologic function may only require minor adjustments (notching) to existing infrastructure rather than complete removal and restoration of a complete heterogeneous topographic landscape. Complete removal of berms and levees may also result in loss of currently occupied habitat by sensitive species. The restoration scenarios proposed aim to reconnect historical channels and floodplains that have been disconnected by levees and berms through simple and minimal terrain modification resulting in reduction of inflows and storage of the pond (Figure 6). Modifications to conveyance levees would increase downstream environmental flows and vernal pool hydroperiods while reducing overall inflow and hydroperiod of the stock pond. Modifications to storage berms would reduce the maximum storage capacity and hydroperiod of the stock pond, providing a more optimal hydroperiod for native species and reducing invasive persistence.

Proposed restoration locations were identified by running the hydrodynamic model under current terrain conditions and identifying areas of flow accumulation at diversion infrastructure as well as comparison against delineated wetland features and DEM generated streamlines to identify hydrologically disconnected areas. Restoration scenario terrains were created by interpolating a new reach between the upstream and downstream historical channels through the existing infrastructure, a method commonly used to insert channel bathymetry into 1D HEC-RAS models. Simple breaks in conveyance levees were proposed to return and redistribute flows to disconnect wetland features. A break in the berm that bounds the pond was also tested in order to reduce the maximum storage capacity and hydroperiod of the pond to better benefit CTS and reduce the persistence of invasive species between seasons (U.S. Fish and Wildlife Service, 2015). Model outputs between the March and April storm events showed vast differences in the amount of total inundated area. The March storm was chosen to simulate under the restoration scenarios as it represented the maximum potential of inundation for the season.

A sensitivity analysis was conducted at single locations in the Upper and Lower Diversions to determine if different sized breaks (3, 5, and 10 m) had a significant effect in additional downstream inundation extent. For each proposed break location, amount of earth moved was calculated using Cut/Fill comparisons between the current and restoration terrains in ArcMap 10.5 for consideration in restoration construction costs. Levee performance was also evaluated by comparing accumulated volume at each proposed break location versus reduction at the corresponding pond inflow and increase in subcatchment outflow.

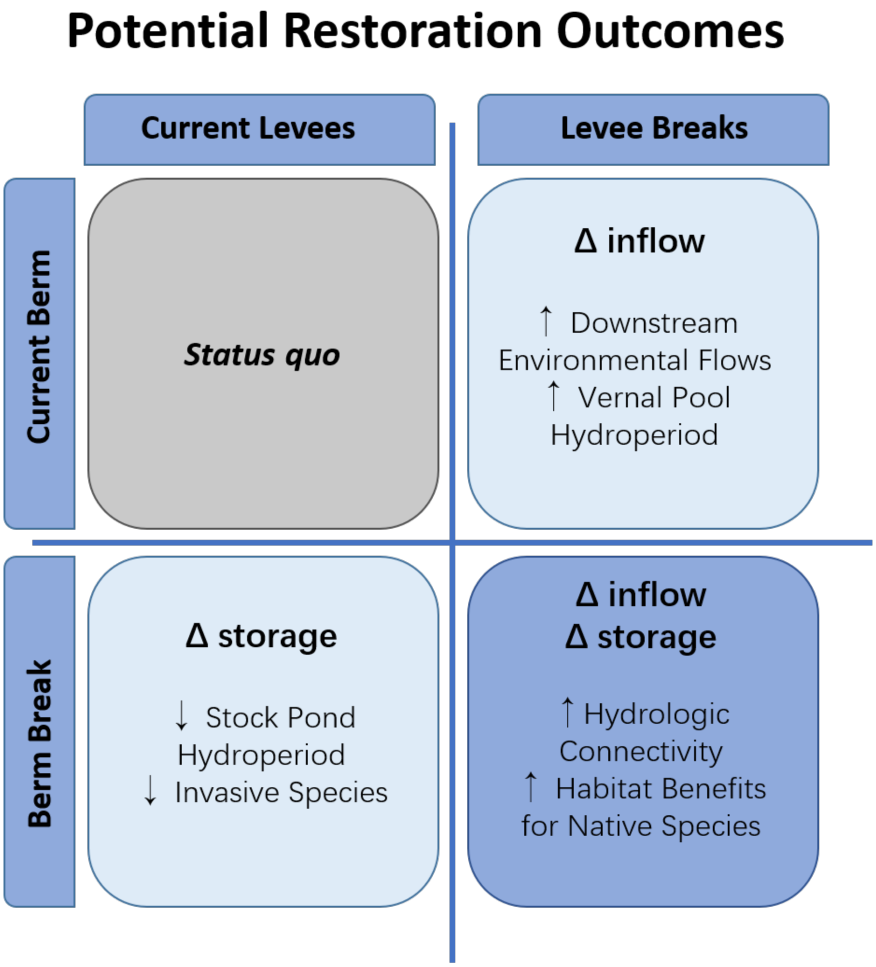

Figure 6 Restoration Potential Matrix showing potential benefits gains from proposed restoration scenarios

CTS Restoration Modeling

A mathematical model was constructed in the statistical computing program R (R Development Core Team, 2008) to estimate stock pond hydroperiod given the range of historical weather patterns observed at the site. Two linear models were constructed using daily changes in pond volume and local weather station data to predict pond filling and drying. The first model used evapotranspiration and maximum wind speed to predict volume of water lost per unit of surface area. The second model estimated the increase in pond volume as a function of precipitation. These models are useful for approximating pond hydrology given various climatic conditions without fine-scale soil and topography data.

Historical weather data from 2002 to 2018 was acquired from the Merced CIMIS (Appendix I) station to simulate daily weather patterns. The probability of precipitation was calculated using the fraction of years that experienced rain for each Julian day. Presence or absence of rain each day was randomly assigned using a draw from a binomial distribution with the probability of rain determined above. If rain was selected for a simulated day, then weather data from a historical day with rain were used. if no rain was determined, then data from a random day were chosen that did not experience rain. This method maintains the relationship between weather observations (temperature, evaporation, and wind speed) while adding stochasticity within a simulated year. Pond volume was then simulated daily using the generated weather data as input for the linear models that estimate drying and filling rates. The maximum number of consecutive days that the pond holds water was recorded as the hydroperiod for that iteration. This simulation was repeated 200 times for each maximum depth considered. This yielded an estimated hydroperiod for each maximum pond depth as well as the variability in that estimate. These values were used to determine an ideal maximum pond volume that would satisfy the minimum requirements of CTS breeding and larval development, while still ensuring that the ponds dried each year, thus, reducing the success of non-native vernal pool inhabitants.

3. Results

Field Work Results

During the 2018 water year two pressure transducers were deployed at the study site, one in the pond to capture hydrologic flux, and the other terrestrially for accurate barometric compensation and calculation of water depth. Loggers were deployed from November 6, 2017-August 10, 2018 and recorded 23 events, spanning 1-3 days, where the pond gained volume from precipitation. There were two instances where precipitation at the UCM weather station and additional pond volume did not correlate, which was attributed to spatially variable rainfall. In both cases, precipitation and pond volume values were very small and would not have been considered as model inputs. Of the 23 events, 5 events contributed greater than 1% gain in maximum pond volume (Table 1). Precipitation values ranges from 18.8-41.2 mm and volume gain ranged from 1.2-19.1% of total pond volume. The two storms that contributed the greatest total volume to the pond were chosen to model. The first occurred over the span of 3 days from March 20-22, 2018 with 40.4 mm of precipitation contributing 19.1% total pond volume (50% total volume gain for season) (Figure 7). The second occurred over the span of 2 days from April 6-7, 2018, with 28.5 mm of precipitation contributing 4.5% total pond volume (12% total volume gain for season) (Figure 8). These model storms comprised 16% and 11% of the cumulative amount (255.8 mm) of precipitation that occurred during the 2018 water year.

The pond gained a total of 24.7 ac-ft and reached a maximum seasonal volume of 23.1 ac-ft (35.8% maximum pond volume) after the April model storm event. The pressure transducer in the pond was exposed in late July 2018 as the pond receded below the instrument elevation and split into multiple pools, the pond dried completely in mid-September 2018. The drawdown from the peak seasonal volume to completely dry took 165 days with and average loss of 0.14 ac-ft/day or 10.5 mm/day. The total hydroperiod of the pond since it last completely dried was estimated to be ~1,055 days from November 2015 – mid-September 2018. Vernal pools within the catchment were inundated for ~40 days in the 2018 water year and ~90 days in the 2017 water year.

Livestock grazed the study site pasture from November 20, 2017 – July 6, 2018. Grazing visitation at the study site was quantified for the 199 days that the game cameras deployment overlapped with potential livestock presence. Maximum group size per day was counted in order to estimate grazer drinking water consumption from the pond. Livestock were present at the pond 150 (75%) out of the 199 counted days and monthly maximum group size ranged from 33-74 individuals. Livestock drinking water consumption for the pond was calculated by multiplying the monthly maximum group size by the number of visitation days and applying a high estimate daily maximum consumption rate for dairy cattle (50 gal/day). Average maximum monthly drinking water consumption was 0.2 ac-ft (0.3% total pond volume). Total estimated consumption for the grazing season was 1.7 ac-ft (2.6% total pond volume). Maximum daily loss was estimated to be ~0.01 ac-ft/day or ~0.75 mm/day, approximately 7% of the total average losses calculated for the last drawdown. Max ETo (CIMIS) during that time period was 8.7 mm/day, or ~83% of total average losses. The remaining 10% of daily losses (~1 mm/day) from the pond were attributed to infiltration into the subsurface.

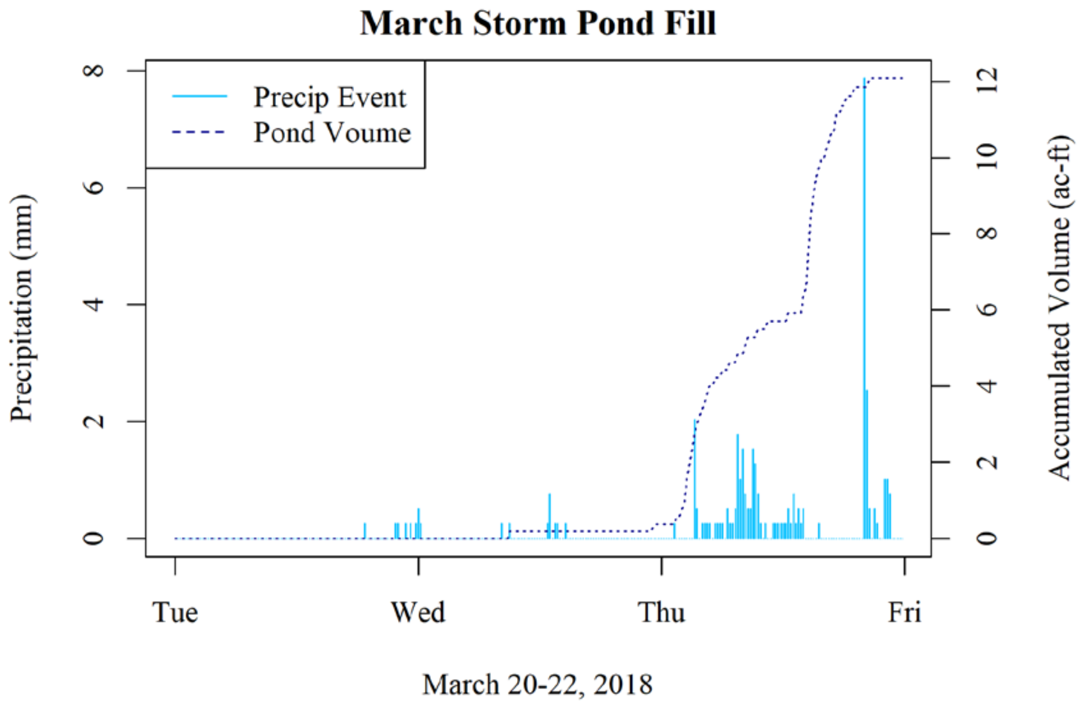

Figure 7 Modeled March Storm Event Precipitation Hyetograph and Volume Gained in Avocet Pond

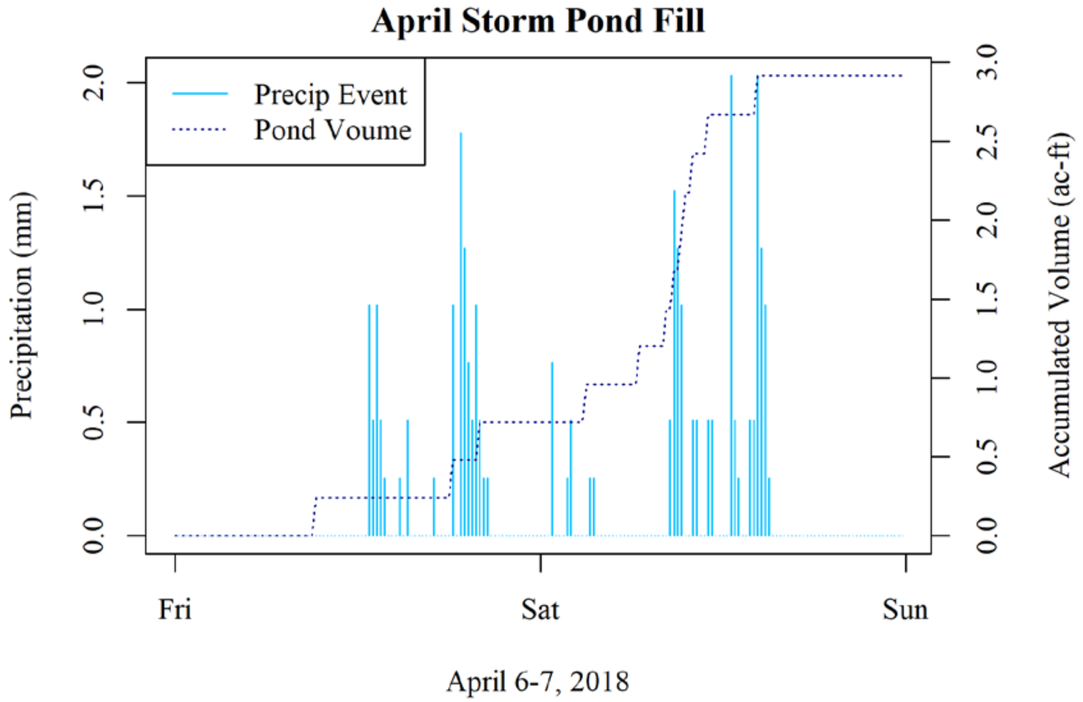

Figure 8 Modeled April Storm Event Precipitation Hyetograph and Volume Gained in Avocet Pond

Table 1 2018 Field Season Precipitation and Pond Filling Events for Model Storm Selection

Event	Start Date	End Date	Event Duration (Days)	Precipitation Event (mm)	% Cumulative Precipitation	Pond Volume Gain (ac-ft)	% Total Season Volume Gain	% Maximum Pond Volume
1	11/9/2017	11/9/2017	1	0.3	0%	0.2	1%	0.3%
2	11/16/2017	11/17/2017	2	11.9	5%	0.4	2%	0.6%
3	11/27/2017	11/27/2017	1	6.1	2%	0.4	2%	0.6%
4	12/20/2017	12/20/2017	1	4.1	2%	0.4	1%	0.6%
5	1/4/2018	1/4/2018	1	5.6	2%	0.2	1%	0.3%
6	1/6/2018	1/6/2018	1	6.9	3%	0.2	1%	0.3%
7	1/8/2018	1/10/2018	3	41.2	16%	1.3	5%	2.0%
8	1/12/2018	1/12/2018	1	0.3	0%	0.2	1%	0.3%
9	1/16/2018	1/16/2018	1	0.3	0%	0.2	1%	0.3%
10	1/18/2018	1/19/2018	2	3.8	2%	0.2	1%	0.3%
11	1/22/2018	1/22/2018	1	0.3	0%	0.0	0%	0.0%
12	1/25/2018	1/25/2018	1	2.8	1%	0.2	1%	0.3%
13	2/23/2018	2/23/2018	1	0.0	0%	0.2	1%	0.3%
14	2/26/2018	2/27/2018	2	12.2	5%	0.4	1%	0.5%
15	3/1/2018	3/3/2018	3	39.6	16%	2.4	10%	3.7%
16	3/13/2018	3/14/2018	1	18.8	7%	0.8	3%	1.2%
17	3/16/2018	3/17/2018	2	6.9	3%	0.4	2%	0.6%
18	3/20/2018	3/22/2018	3	40.4	16%	12.3	50%	19.1%
19	3/24/2018	3/24/2018	1	8.6	3%	0.5	2%	0.7%
20	4/6/2018	4/7/2018	2	28.5	11%	2.9	12%	4.5%
21	4/12/2018	4/12/2018	1	0.8	0%	0.3	1%	0.4%
22	4/16/2018	4/17/2018	2	10.7	4%	0.5	2%	0.8%
23	5/2/2018	5/2/2018	1	0.3	0%	0.2	1%	0.4%
24	5/25/2018	5/25/2018	1	1.5	1%	0.2	1%	0.3%

Model Performance

Solution convergence was achieved through iterative adjustments in model cell size, cell tolerances, and time step control. The model volume accounting error was 0.05% for March Storm and 0.15% for April Storm model simulations. The model domain contained approximately 143,000 computational cells with computation times ranging from 30min-1hr for WSE restart files, 9-10 hrs for April Storms, and 11.5-12.5 hrs for March Storms. Rainfall loss approximations were back calculated using pond volume gain during the storm as a percentage of diverted catchment area. The March storm was simulated at 54% of total (Figure 9) and the April storm was simulated at 18% of total (Figure 10) to achieve model ending pond WSE calibrated to field measurements. Rainfall was abstracted at a constant rate, reducing each rainfall timestep event by the back calculated loss percentage. All models were simulated using the Diffusion Wave equation set, as simulations using the Full Momentum equation set were unable to provide a numerically stable solution.

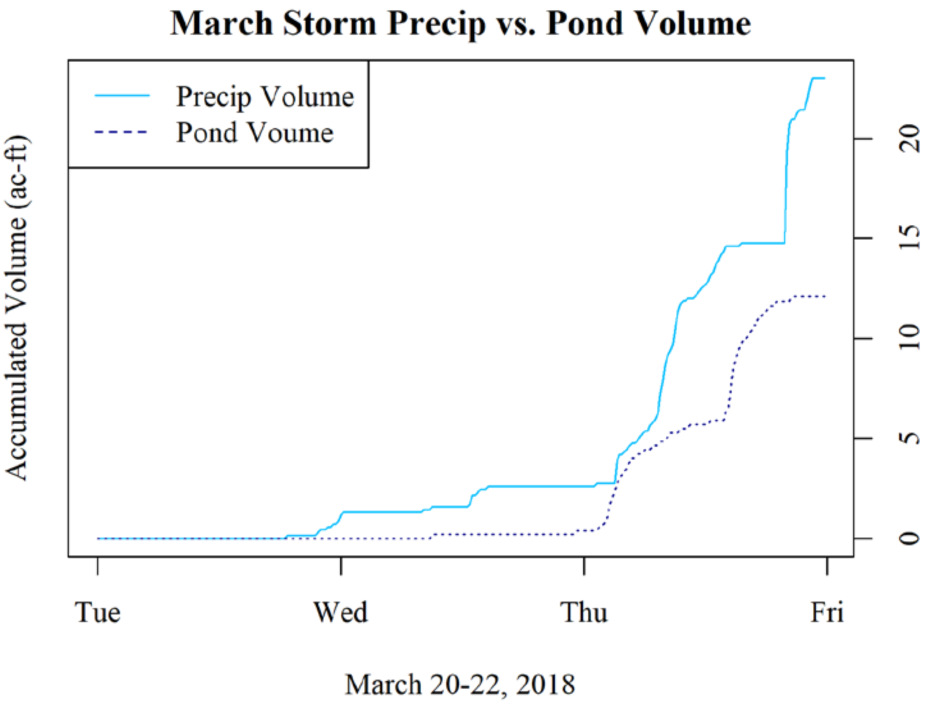

Figure 9 Accumulated volume of precipitation in the upstream catchment diversions and volume captured in the pond during the March 20-22 storm event.

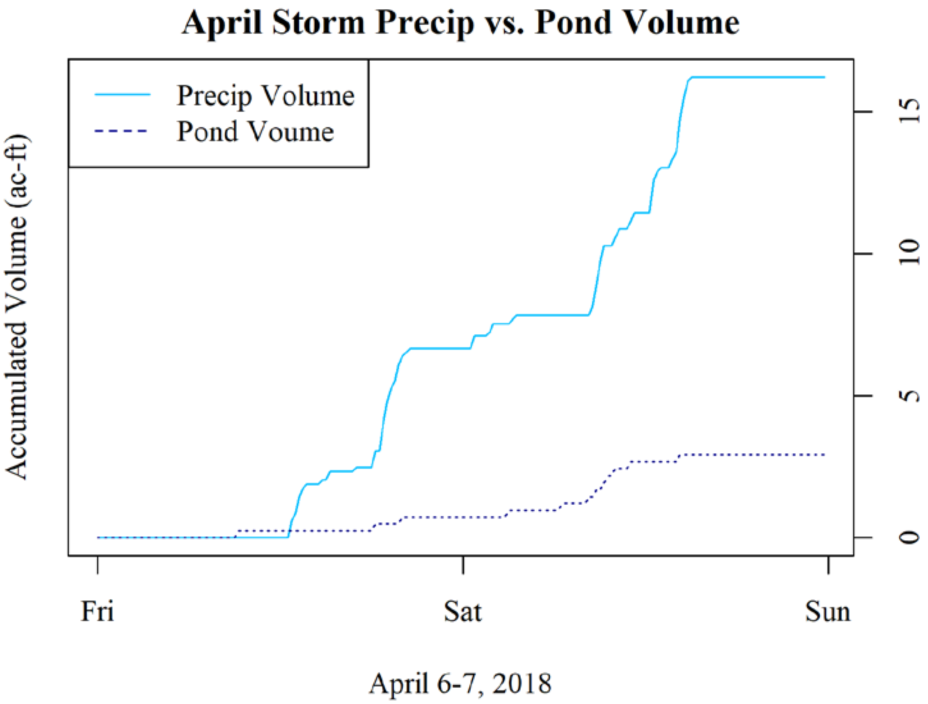

Figure 10 Accumulated volume of precipitation in the upstream catchment diversions and volume captured in the pond during the April 6-7 storm event.

Wetland Delineation Classification Accuracy

In order to evaluate the potential restorable acres of wetland habitat, the model inundation outputs were spatially compared against a delineated wetland feature layer. The layer was heads up digitized from aerial imagery collected in 2001 and encompasses a broad region of Eastern Merced County (EIP Associates, 2002). These spatial data, referred to here as EIP Wetlands, depict features considered to be wetlands for regulatory purposes verified by the U.S. Army Corp of Engineers, and is currently used as reference for wetland mitigation accounting and credits by the University of California, Merced. Delineated wetland types consist of canal wetlands, clay playas, clay slope wetlands, linear features, pool/swale complexes, seasonal wetlands, stock ponds, swale wetlands, and vernal pools. This analysis used these delineations as a means to understand the benefit of potential rewetting as a function of wetland type.

The full EIP Wetlands dataset contains 83,723 delineated wetland features, 8,094 (~10%) of which are located within the Reserve. Only 7,723 (9%) features from the full dataset were field assessed for correct wetland type classification, 5,092 (66%) of which were located within the Reserve. For all assessed features, classifications were correct 78% of the time, with 99% of the correct classifications designated as vernal pools. For assessed features within the Reserve, classifications were correct 79% of the time with 100% of the correct classifications designated as vernal pools. Delineated wetlands features were only field assessed on the west side of the Reserve, there were no field assessments conducted within the model domain or greater watershed.

Visual Corroboration and Model Validation

Using UAV aerial imagery and video collected between modeled storm events, model results generally conformed to observed conditions. Model output inundation area polygons generally matched with inundated pool edges, but multiple smaller polygons mismatched in swale areas that visually appeared dry. These smaller polygons represented very shallow ending inundation depths which most likely infiltrated or evaporated soon after the storm event. Vernal swales are small drainage ways that hydrologically interconnect vernal pools that can remain saturated during the growing season but only flow during and for a brief period following heavy rains (Vollmar, 2002). Inundation polygon boundary agreement with the pond boundary edge was particularly important in assessing accuracy of the DEM bathymetry merge as model calibration was based on recorded pond WSE pre- and post-storm events.

The Cohen's kappa coefficient was used to compare model inundation classification to the EIP Wetland layer and a layer of Expected/Observed inundation generated by buffering grouped orders of streamlines. Timelapse imagery taken during the modeled March storm showed the two pond inflows overtopping the channel, lending evidence to the assumption that other channels within the model domain would also be inundated during the storm event. Buffer widths from 1-3 m were chosen based on general maximum widths of defined green swales measured from high-resolution imagery collected during the green-up and brown-down of the field season. Comparisons of inundation classification agreement were assessed for 1,000 random points generated within each subbasin including the pond and surrounding overland flow upland area. The model showed moderate agreement ($\kappa = 0.53$) with both the EIP Wetland layer (Table 2) and Expected/Observed Inundation layer (Table 3) across the full model domain, however model agreement varied across the individual subbasins.

Table 2 Model Validation Cohen's Kappa: Model vs. EIP Wetlands

EIP Wetlands	**Upper Side**	**Lower Side**	**Lower Pond**	**Lower Floodplain**	**Upper Pond**	**Upper Floodplain**	**Model Domain Subbasins**	**Pond**	**Model Domain Full**
Observed Proportionate Agreement	0.94	0.87	0.92	0.77	0.94	0.78	0.87	0.86	0.87
Expected: Inundated	0.01	0.02	0.00	0.03	0.00	0.04	0.01	0.24	0.03
Expected: Not Inundated	0.86	0.75	0.87	0.66	0.91	0.64	0.78	0.26	0.69
Overall Random Agreement	0.86	0.77	0.87	0.70	0.91	0.68	0.79	0.50	0.72
Cohens Kappa	0.54	0.42	0.37	0.24	0.36	0.31	0.37	0.72	0.53
Accuracy	0.94	0.87	0.92	0.77	0.94	0.78	0.87	0.86	0.87
Misclassification Rate	0.06	0.14	0.08	0.23	0.06	0.22	0.13	0.14	0.13
Sensitivity	0.76	0.45	0.60	0.48	0.60	0.56	0.53	0.80	0.66
False Positive Rate	0.05	0.06	0.06	0.18	0.05	0.18	0.10	0.07	0.09
Specificity	0.95	0.94	0.94	0.82	0.95	0.82	0.90	0.93	0.91
Precision	0.45	0.55	0.31	0.31	0.28	0.36	0.37	0.93	0.57
Prevalence	0.06	0.15	0.05	0.14	0.03	0.15	0.10	0.53	0.16

Table 3 Model Validation Cohen's Kappa: Model vs. Expected/Observed

Expected/Observed	**Upper Side**	**Lower Side**	**Lower Pond**	**Lower Floodplain**	**Upper Pond**	**Upper Floodplain**	**Model Domain Subbasins**	**Pond**	**Model Domain Full**
Observed Proportionate Agreement	0.85	0.87	0.90	0.83	0.89	0.82	0.86	0.87	0.86
Expected: Inundated	0.02	0.02	0.01	0.03	0.01	0.03	0.02	0.19	0.03
Expected: Not Inundated	0.75	0.75	0.80	0.68	0.81	0.67	0.75	0.32	0.67
Overall Random Agreement	0.77	0.77	0.81	0.71	0.82	0.70	0.76	0.51	0.71
Cohens Kappa	0.33	0.45	0.46	0.41	0.35	0.42	0.40	0.73	0.53
Accuracy	0.85	0.87	0.90	0.83	0.89	0.82	0.86	0.87	0.86
Misclassification Rate	0.15	0.13	0.10	0.17	0.12	0.18	0.14	0.13	0.14
Sensitivity	0.32	0.47	0.45	0.72	0.31	0.75	0.49	0.89	0.63
False Positive Rate	0.05	0.06	0.04	0.16	0.03	0.17	0.08	0.15	0.09
Specificity	0.95	0.94	0.96	0.84	0.97	0.83	0.92	0.85	0.91
Precision	0.58	0.59	0.60	0.38	0.63	0.39	0.48	0.81	0.60
Prevalence	0.17	0.15	0.12	0.12	0.13	0.13	0.14	0.41	0.17

Sensitivity Analysis: Volume Removed vs. Acres Rewetted

A sensitivity analysis was performed on single levee breaks in the Lower and Upper Levees of varying widths (3, 5, and 10 m) to assess differences in downstream inundated area, pond inflow volumes, and catchment outflow volumes. In the Upper Levee, 3-5 m break widths resulted in the same amount of inundated area (0.72 ac). The 10 m break only inundated an additional 0.05 ac than the smaller breaks. All break widths decreased accumulated volume at the Upper Inflow by 23-42% and increased volume at the Upper Outflow by 24-41%. In the Lower Levee, break widths resulted inundated areas ranging from 2.5-3 ac. The 10m break inundated slightly less acreage (0.08 ac) than the smaller breaks. All break widths decreased volume at the Lower Inflow by 86% and increased volume at the Lower Outflow 186-202%. Between both break locations, the 10 m levee breaks involved the removal of about twice the amount of earth than the smaller break widths (average ~19 m^3) (Tables 4-5).

Table 4 Inundation Acreage vs. Volume of Levee Removed for Current Conditions and Restoration Scenarios.

Current Conditions: Inundation Inside and Outside of EIP Delineations				
Location		Current EIP Inundation (ac)	Current Inundation Outside EIP (ac)	Combined Current Inundation (ac)
Upper Floodplain		5.14	8.51	13.65
Lower Floodplain		3.28	6.36	9.64
Sensitivity Analysis				
Restoration Location	Levee Volume Removed (m^3)	Additional EIP Inundation (ac)	Additional Inundation Outside EIP (ac)	Combined Additional Inundation (ac)
Upper Break 1 (3m)	18.67	0.19	0.53	0.72
Upper Break 1 (5m)	23.90	0.18	0.54	0.72
Upper Break 1 (10m)	40.47	0.24	0.68	0.92
Lower Break 1 (3m)	18.74	0.51	2.3	2.81
Lower Break 1 (5m)	25.15	0.55	2.49	3.04
Lower Break 1 (10m)	42.87	0.47	2.01	2.48
Levee and Berm Break Analysis (5m Breaks)				
Restoration Location	Levee Volume Removed (m^3)	Additional EIP Inundation (ac)	Additional Inundation Outside EIP (ac)	Combined Additional Inundation (ac)
Upper Break 1	23.90	0.18	0.54	0.72
Upper Break 2	13.48	0.15	0.1	0.25
Upper Break 3	20.94	0.3	0.68	0.98
Upper Break 4	11.33	0.47	1.16	1.63
All Upper Breaks	69.65	0.68	1.58	2.26
Lower Break 1	25.15	0.55	2.49	3.04
Lower Break 2	24.36	0.38	2.35	2.73
Lower Break 3	13.87	0.37	0.98	1.35
Lower Break 4	20.67	0.33	0.33	0.66
All Lower Breaks	84.05	0.92	2.76	3.68
All Levee Breaks	153.70	1.6	4.34	5.94
Berm Break	223.69	0.22	0.52	0.74
All Breaks	377.39	1.6	4.41	6.01

Table 5 Accumulated Volume Reduction for Restoration Scenarios

<table>
<tr><th colspan="5">Current Conditions</th></tr>
<tr><th></th><th>Lower Inflow</th><th>Lower Outflow</th><th>Upper Inflow</th><th>Upper Outflow</th></tr>
<tr><td>Accumulated Volume (ac-ft)</td><td>6.51</td><td>2.81</td><td>4.15</td><td>3.47</td></tr>
<tr><th colspan="5">Sensitivity Analysis</th></tr>
<tr><th>Location</th><th>Lower Inflow</th><th>Lower Outflow</th><th>Upper Inflow</th><th>Upper Outflow</th></tr>
<tr><td>Location 1 (3m)</td><td>-86%</td><td>187%</td><td>-24%</td><td>24%</td></tr>
<tr><td>Location 1 (5m)</td><td>-86%</td><td>186%</td><td>-23%</td><td>28%</td></tr>
<tr><td>Location 1 (10m)</td><td>-86%</td><td>202%</td><td>-42%</td><td>41%</td></tr>
<tr><th colspan="5">Levee and Berm Break Analysis (5m Breaks)</th></tr>
<tr><th>Location</th><th>Lower Inflow</th><th>Lower Outflow</th><th>Upper Inflow</th><th>Upper Outflow</th></tr>
<tr><td>Location 1</td><td>-86%</td><td>186%</td><td>-23%</td><td>28%</td></tr>
<tr><td>Location 2</td><td>-98%</td><td>225%</td><td>-3%</td><td>3%</td></tr>
<tr><td>Location 3</td><td>-25%</td><td>43%</td><td>-16%</td><td>8%</td></tr>
<tr><td>Location 4</td><td>-9%</td><td>19%</td><td>-95%</td><td>112%</td></tr>
<tr><td>All Levee Breaks</td><td>-99%</td><td>226%</td><td>-95%</td><td>119%</td></tr>
<tr><td>Berm Break</td><td>-3%</td><td>385%</td><td>8%</td><td>-13%</td></tr>
<tr><td>All Breaks</td><td>-99%</td><td>250%</td><td>-95%</td><td>116%</td></tr>
</table>

Levee Break Analysis: Individual and Combined Impact

For the March Storm under current conditions 5.14 ac of EIP Wetlands and an additional 8.51 ac outside the delineations were inundated in the Upper Floodplain. In the Lower Floodplain, 3.28 ac of EIP Wetlands were inundated and an additional 6.36 ac were inundated outside of the delineations.

Individual 5m levee break performance was assessed and compared to maximum restoration scenarios with All Levee breaks (Upper and Lower) or All Breaks (Levees and Berm) (Figure 11) implemented. Individual break outflow volume was typically reduced when other breaks were in present within the same infrastructure, except Upper Break 1, which released more water downstream under both increased restoration scenarios. The Berm Break exhibited the most loss of function when evaluated along with other levee breaks.

For individual breaks in the Upper Levee, pond inflows were reduced 3-95% and downstream flows increased 3-112% depending on which location is breached. Under the All Levee scenario flows released downstream at the Upper Outflow increased 119%. Additional EIP Wetland inundation in the Upper Floodplain ranged from 0.15-0.47 ac depending on break location, combined additional inundation ranged from 0.25-1.63 ac. Although levee breaks were estimated to be the same approximate width, levee volume removal ranged from 11-24 m^3 due to varying levee height and topography. Under the All Levee and All Break scenarios ~70 m^3 of levee removal would result in 0.68 acres of additional inundation in the EIP wetlands and a combined total of ~2.26 acres of additional area inundated in the Upper Floodplain.

For individual breaks in the Lower Levee, pond inflows were reduced 9-98% and downstream flows increased 19-225%, depending on which break location was implemented. Under the All Levee and All Break scenarios downstream, flows increased 226-250% and the Lower Outflow. Additional EIP Wetland inundation in the Lower Floodplain ranged from 0.33-0.55 ac depending on break location, and combined additional inundation ranged from 0.66-3.04 ac. Under both the All Levee and All Break scenarios 0.92 ac of additional EIP Wetland and ~2.77 ac of additional area were inundated in the Lower Floodplain. Levee volume removed ranged from 14-25 m^3 (84 m^3 combined) for individual levee breaks in the Lower Levee. The Berm Break by itself constitutes 60% (224 m^3) of volume removed in the All Break scenario, more than the combined total of all levee breaks in the Upper and Lower Levees (~154 m^3).

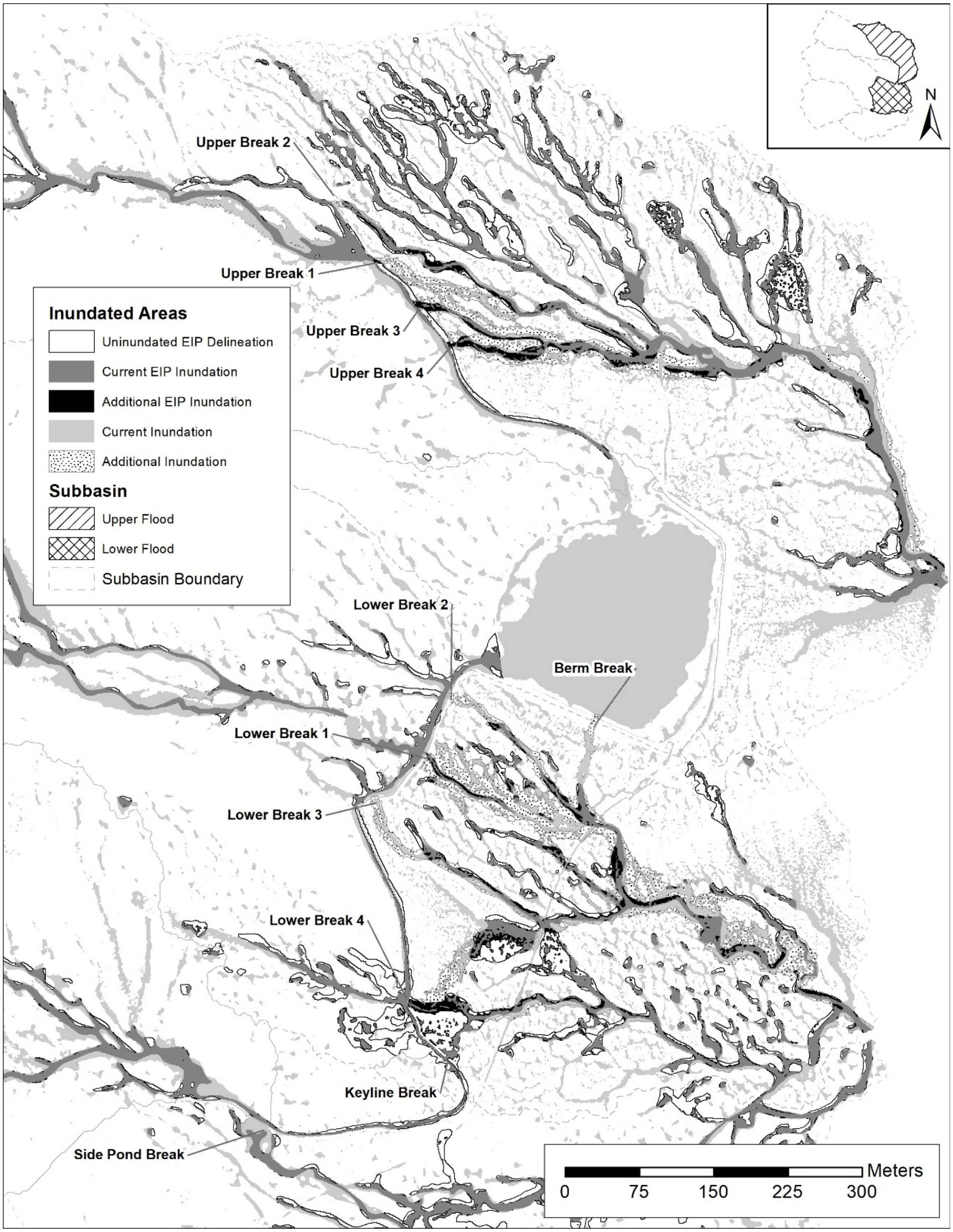

Figure 11 March Storm Inundation Map under All Break Restoration Scenario

Berm Break Analysis: CTS Hydroperiod Modification

Preliminary modeling conducted by project collaborators at UCLA, using the storage curve generated from the pond bathymetry and weather data from nearby stations (CDEC and CIMIS), proposed a maximum pond volume of 1200-1300 m^3 (~1 ac-ft) in order to achieve a 150-day hydroperiod (30 days of CTS egg development and 120 days of larval growth) at least 50% of the time.

The Berm Break was inserted at a WSE of 121.24 m (corresponding volume = 1137 m^3) and the altered terrain was simulated under the March Storm hydrograph. At the end of the model run, pond output volumes were split between two ponds with a combined volume of 1734 m^3. The upper pond had a WSE of 121.45 m and volume of 697 m^3. The lower pond had a WSE of 121.24 where the berm cut was inserted and a volume of 1037 m^3. The storage curve for the pond combined volumes of areas that separate during the drawdown. Additional models were run at 5 cm elevation increments to visually assess pond separation and convergence. The pond completely separates at a WSE between 121.45m and 121.50m, higher than the targeted berm cut. The upper pond splits again at a WSE of 121.25m, with the smaller portion containing the deepest point of the original upper pond.

4. Discussion

Quantifying and Comparing Restoration Benefits

The results indicate that small terrain modifications in existing infrastructure around Avocet Pond can be effectively modeled with an explicit 2D hydrodynamic model to identify changes in inundation and flows. Modeling the largest storm event of the season provided insight into the maximum potential and tradeoffs of inundation across the site, as soil saturation, inundation, connectivity, and transfer were greatest at that time. However, quantifying the overall restorative benefits of individual break locations is not as simple as estimating the total amount of wetland acreage that can be rewetted. Levee breaks will inundate more downstream area when implemented on an individual basis as opposed to when other breaks are also present in the same conveyance system. Due to the shallow interconnected hydrology of the wetlands, inundated areas from multiple levee breaks overlap, making it difficult to identify the unique contributions from each restoration location. Tradeoffs must be presented and evaluated for each restoration location regarding amount and quality of wetlands rewetted, potential inflow reduction to the pond, amount of water returned to the downstream environment, and construction costs and impacts to modified habitat that may currently be occupied by sensitive species. The environmental flows and benefits will differ season to season based on the timing, intensity, and duration of storm events and antecedent soil moisture conditions.

Proposed levee breaks that were geographically closest to the pond inflows reduced inflows 95-98%. In both cases, the breaks provided some of the largest amounts of increased downstream inundated acreage, however visual observations of the simulated maximum inundation extent overlaid with high resolution imagery shows the area inundated by Lower Break 2 had been previously disturbed and scraped for construction of the berm that bounds the pond, indicating reduced restoration potential. In contrast, Upper Break 4 inundates the largest additional amount of EIP Wetlands and total combined additional downstream acreage, providing ones of the better tradeoff ratios between acres rewetted and volume levee removed. This location also inundates the largest unique acreage (~1 ac) that is not receive increased flows from other restoration scenarios. However, the effect of fully reducing inflows to the pond must be also considered as the pond currently serves as occupied breeding habitat for CTS, therefore implementing breaks in these locations may not be ideal.

Lower Break 1 provides the maximum combined additional inundation acreage in the Lower Floodplain without fully reducing pond inflows. Implementing breaks geographically further away from the Lower Inflow (Lower Break 3 or 4) did not have much of an effect on reducing overall inflows to the pond, however additional delineated wetlands were inundated that did not receive flows from other restoration scenarios that redirected higher volumes of water.

Upper Break 1 was initially proposed and tested due to the large accumulation of upstream flows in the area, however it did not inundate as much area as breaks geographically closer to the Upper Inflow and only reduced pond inflows by 25%. Upper Break 2 provided the least benefit, with minimal inundated acreage and reductions to pond inflows. Upper Break 3 provided the second highest amount on inundated acreage in the Upper Floodplain without substantially reducing pond inflow volume at the Upper Inflow.

Notching the berm to modify the maximum storage and overall seasonal hydroperiod of the pond releases the most water downstream but does not provide more additional rewetted acreage than other proposed levee breaks (Lower Break 1) which inundate the floodplain from which flows are currently diverted. Additionally, when the Berm Break was implemented on its own it only released flows back into one of the hydrologically disconnect subbasins, bypassing the Upper Floodplain entirely. The feasibility of the notching the berm at this site should be considered given that the modification requires a larger amount of earth removed than all individual levee breaks combined and provides minimal downstream benefits in the targeted wetland restoration areas.

Construction costs for restoration depend on how much work is necessary, in this case, how much earth needs to be moved. Overall, the removal of more earth did not necessarily equate with increased wetland inundation (Figure 12). Individual levee breaks with approximately the same amount of earth moved differed in the amount of downstream area inundated. When all individual levee breaks were combined, the inundated acreage was only double of what the most effective individual break was capable of inundating but required ~6x the amount of earth removed. The Berm Break required ~10x more earth removal than the average individual levee break and did not inundate a substantial amount of acreage. When combined with all levee breaks, the Berm Break did not increase additional inundated acreage even though a substantial additional amount of earth was removed. Additional construction and maintenance costs would also need to be considered depending on the degree to which hydrologic connectivity is restored to natural channels that bisect roads downstream of the current diversions. Increased flow velocities may intensify existing road cuts and affect road usability and access to eastern edges of the Reserve.

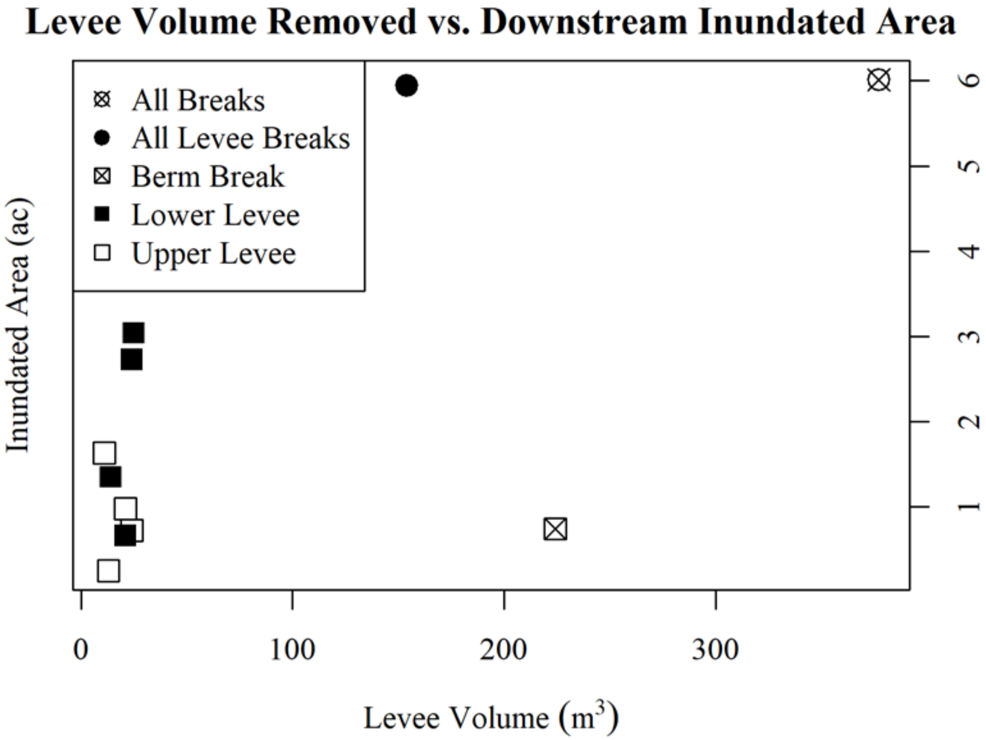

Figure 12 Relationship between levee volume removed and downstream inundated area for individual and combined Levee and Berm Breaks

Restoration for Targeted Species

Better understanding of water in space and time helps inform effective management decisions. The majority of the water in Avocet Pond is lost to evaporation and could be better distributed across the landscape for improved habitat conditions and persistence of native species. Refining ideal restoration scenarios beyond rewetted acreage potential within the current model domain could be further informed by analysis of pool geomorphic setting and distribution in association with surveyed species occurrences. Increased pool inundation coupled with managed grazing would reduce non-native plant species, providing competitive release for native species to utilize available niche space. Reduced stock pond hydroperiod would benefit native CTS adapted to utilize these modified systems by reducing the persistence of invasive species that require perennial water sources for establishment and persistence.

Attempts to model alterations to the berm in order to modify maximum pond storage to create an ideal hydroperiod for breeding and developing CTS were complicated by the underlying bathymetry of the pond and underestimated target maximum volumes. The pond was constructed across a low topographic saddle resulting in the larger stock pond dividing into multiple smaller pools as it dries down to shallow depths. The volumes and surface areas of these separate pools were computed cumulatively in the storage curve generated from the pond bathymetry.

The current hydroperiod model was developed for smaller ponds, so there are many caveats to consider when applying this model to the study site. Historical precipitation was not perfectly correlated with the site precipitation. Due to the seasonality of pond dynamics during the period of data collection and modeling timeline, pond drawdown data were not collected in full. Soil wicking accelerates drying at very low levels, and it is unknown at what volume the smaller pools would become functionally dry. The potential benefits of multiple ponds would be the ability of CTS larva to disperse and mix between the ponds which would reduce the risk of total breeding failure given stochastic events such as predation or early dry down of a shallower pond. A drawback would be the potential for eggs laid in the shallow areas between ponds to be exposed and dry up as the larger pond recedes and splits.

The model estimated ideal maximum pond volume was not realistic given actual drawdown rates observed during the 2018 water year in which 23x the proposed maximum storage volume was removed from the pond over the duration of the target hydroperiod. As some of the levee restoration scenarios significantly reduce inflow volumes to the pond, modifying the berm may be unnecessary given that the hydroperiod of the pond will already be reduced from current conditions. Other stock ponds within the Reserve may be better candidates for this type of restoration as they are only modified with berms and have less complicated underlying bathymetry. There are also an estimated 1156 additional stockponds in the EIP layer for broader applicability of this restoration methodology at a landscape scale.

Model Methodology: Advantages and Caveats

Modeling this geographically isolated wetland system using 2D direct rainfall methods in HEC-RAS was an appropriate choice given the small data requirements of the model and the lack of hydrologic data available to collect at the study site. Using the 2D model, results are delineated down to the 2D cell resolution hydrologic models unlike lump sum or semi-distributed catchment models. The inundation mapping capabilities available through the RAS Mapper interface provide invaluable visual insight for comparison of results, terrain manipulation, and identifying hydrologic behavior under different restoration scenarios across the model domain. The current version of the program does not account for infiltration or spatially variable precipitation; however, both of these capabilities are currently being developed and are expected to be incorporated in the next version release of the program. Given the relative nascency of this type of modeling approach and our novel application of this program to this type of landscape for restoration assessment potential there are limited published data supporting this approach or guidance for calibration and model validation (Babister & Barton, 2012).

Model Validation: Inundated Classification

Model inundation outputs were validated against the EIP Wetland layer and a generated Expected layer of inundation informed from field observations. It was difficult to estimate the total amount of inundated area during the storm from aerial imagery collected 5-13 days after the event, as most flows accumulate in swales and are conveyed downstream rather than captured in depressional storage. Coarsely delineated EIP wetland features often did not align with visible channels in aerial imagery and generally overestimated channel features to an exaggerated extent. Streamline buffers generated in the expected layer were generalized by grouped stream order rather than upstream drainage area and did not estimate areas of inundation outside of channelized flow. Overall concordance for both layers was high, but largely driven by the intersection of non-inundation (Appendix III). Lack of concordance in the inundated category is largely attributed to areas of shallow overland flow generation outside of channels and swales, including the interstitial spaces between mima mounds, processed expected during an inundating storm event that can be modeled, but not easily captured or quantified after the event.

Model outputs suggest areas of inundation outside of the currently delineated wetlands features and expanded areas of inundation as a result of the different restoration scenarios. It is possible that these currently inundated areas may represent undermapped wetland features given the validity and accuracy issues of the delineated wetlands layer currently used for comparison against model outputs and for mitigation accounting by the University. The modeled additional inundation areas may be indicative of potential wetland restoration.

The objective of the modeled restoration scenario is to reconnect historical channel flow to increase downstream inundation, which necessitates the proper delineation of these types of wetlands in order to accurately estimate restorable acreage. Mitigation credit is highly dependent on the proper identification of vernal pools and wetlands (Mead, Witham, Bauder, Belk, & Ferren, 1996). Given the high cost range ($60,000-$384,250 per acre) that credits have been sold for in the Central Valley (Barati, 2015) better certainty and delineation of what exists at the site is needed prior to methods of and costs of compensatory mitigation can be established if this methodology is applied in the context of assessing potential credit allocation for wetland restoration.

Recommendations for Further Research and Model Expansion

Improved Model Terrain

The current model terrain may be improved in several ways that could result in better resolved model outputs, such as using higher accuracy input terrain datasets and continued refinement of the 2D grid cells within the model domain. Good topographic data and land use information which informs hydraulic roughness coefficients are ultimately what route the hydrologic flows. Incorporating a DEM derived from airborne Light Detection and Ranging (LiDAR) data may improve the vertical accuracy of the terrain model. LiDAR-derived DEMs typically provide a vertical accuracy of ± 0.15 m (Lang, McDonough, McCarty, Oesterling, & Wilen, 2012). Vertical accuracy from the SfM-derived DEM was ± 0.35 m within the model domain and ± 0.39 m across the entire catchment. Due to limitations in UAV flight time capabilities the SfM DEM was created using four separate, overlapping flight areas, collected on different days. Vertical inaccuracies were greater at the outer edges of the catchment and in overlapping flight areas. Depending on the aerial platform, it is possible that LiDAR could be collected over the entire study site in a single time period, reducing variation and error introduced by merging multiple datasets. The model input terrain was a merge of the SfM DEM and a sonar-derived DEM of the pond bathymetry, resulting in loss of resolution of pond inflow channels and abrupt slope breaks at the merged edges of the two datasets. It would be advantageous to collect a DEM when the stock pond is empty in order to get a continuous rather than interpolated terrain dataset. Alternatively, a continuous terrain layer could be collected while stock ponds are inundated with green or bathymetric LiDAR, which penetrates water and is reflected by the bottom surface.

Improved Runoff Estimations

Runoff is dependent on the cell area which needs to be commensurate with the hydrologic process being modeled. Further refinement of the 2D cell areas by increasing cell resolution or inserting additional breaklines along hydraulic routing features such as streamlines and swales, may improve resolution of the results with the tradeoff of increased computation time. Alternatively, topographic detail and characteristics of interest may be lost if grid spacing is increased (Zhang & Chu, 2015) in an effort to increase model domain area and/or decrease computation time. This tradeoff must be considered if the model is to be expanded to incorporate the entire watershed down to the confluence with Black Rascal Creek or applied to other watersheds impacted by stock ponds within the Reserve.

Rainfall losses were applied at a constant rate throughout the duration of the modeled storm events, however infiltration is not constant, and decreases during a storm event. Surface runoff is closely related to infiltration capacities, which are not constant in space or time and are a complex function, principally of soil moisture (Betson, 1964). Infiltration is ignored in the current model with the assumption that losses have been computed and only excess precipitation is being applied and observed at only the surface level. However, it is equally important to understand how catchments retain water as well as how it is released (McNamara et al., 2011). Storage thresholds that control the release of water exist at scales as small as the soil matrix and as large as the catchment (Spence, 2010). Model outputs may have differed is rainfall abstraction was applied as a function of soil moisture. However, estimating antecedent conditions prior to modeled storm events is complicated by the extent and spatial soil moisture variability of multiple soil types encompasses in the model domain and broader watershed.

Informed Subsurface Dynamics

Understanding connectivity at this range of scales requires basins to be instrumented within the context of a water budget investigation, with measurements taken within key catchment units. Refining the resolution of the soil data through site remapping of the implementation of a network of soil moisture sensors or would give insight into catchment connectivity and storage as well as antecedent condition and the evolution of soil moisture patterns during storm events. High resolution soil moisture maps may also be derived from remote sensing products acquired prior to modeled storm events.

Subsurface dynamics would be further investigated with the use of ground penetrating radar (GPR) to map the underlying confining layer. Use of this technology has already been applied to other sites on the Reserve (Tham, 2018). Understanding the integrity of the confining layer at modified sites may influence restoration decisions based on habitat quality. Knowledge of the depth to the subsurface may help identify pools that may more readily inundate with restored flows.

Improved Hydrologic Data

Boundary conditions applied are important in determining the results produced by the model. Precipitation was the sole hydrological model input. Accurate measurement of precipitation is vital in hydrologic modeling studies, however historical precipitation measurements are systematically deficient due to wind induced undercatching in rain gauge networks (Pollock et al., 2014). The precipitation data were acquired from the UC Merced CDEC weather station location ~4 miles from the study site. There were two instances of spatially variable rainfall exhibited across that distance in which precipitation and pond filling events did not correlate. More accurate input parameters may be obtained by installing a rain gauge at the study site to reduce the mismatch due to spatial variability.

Hindcasting pond dynamics using the current weather station input is not recommended given the short timeline of available data (2012-current) incorporates mostly drought years. Pond fill and drawdown dynamics can be more precisely modeled with improved, longer term data sets and increased instrumentation of the site to get a better idea of antecedent conditions prior to precipitation events and seasonal soil moisture patterns. Estimating pond fill rates is difficult to predict as precipitation and antecedent soil moisture conditions vary from year to year; however, applying drawdown rates calculated from pressure transducers may be applicable in estimating pond hydroperiod after final precipitation filling events of the season.

Reserve Data Clearinghouse

The recent establishment of the Merced Vernal Pool and Grassland Reserve within the UC Natural Reserve System and its adjacency to the UC Merced campus provides a unique and highly accessible opportunity for collaborative, interdisciplinary landscape scale research of rare, threatened, and endangered plants, animals, and habitats. Planning reports, annual assessments, and handful of undergraduate and graduate student research projects have accumulated a wealth of data that is not easily accessible or distributable. Having an organized database server to house common and project specific geospatial and tabular environmental data would promote data sharing and accessibility and facilitate interdisciplinary collaboration. Accumulating a local body of knowledge and data provides opportunities for long term studies relationships between catchment form and function (McNamara et al., 2018). From a broader perspective, the Reserve database would ideally be housed within a larger regional data clearinghouse specific to California vernal pools, similar to the Sierra Nevada Meadows Data Clearinghouse ("Sierra Nevada Meadows," 2016) which houses and maintains data on a similar ephemeral wetland ecosystem.

5. Conclusion

A 2D hydrodynamic model was developed to assess the restorative potential of a vernal pool complex at Avocet Pond in the Merced Vernal Pools and Grassland Reserve. In this currently modified system, levees disconnect natural channels and reroute overland flows into stock ponds which behave as reservoirs, removing water from downstream landscape processes. Base case hydroecological conditions were established as the formative basis for evaluating the benefit of various restoration scenarios. Proposed restoration scenarios implemented simple terrain modifications such as small breaks in conveyance levees or notching stock pond berms. Model simulations suggest that historical flow paths can be reconnected through minimal terrain alteration resulting in increased inundation to wetlands and other downstream environments and reduction of overall stock pond inflows and hydroperiod. Modifications to conveyance levees increased inundated area and downstream flows and reduced stock pond inflows to varying degrees depending on location within the conveyance system. Modifications to the storage berm effectively reduced stock pond capacity but provided the least associated downstream restoration benefits. Increased earth removal depending on restoration scenario and location did not necessarily inundate more downstream acreage.

The results and information obtained from this study can be used as an example for how to best manage and restore conserved vernal pool landscapes whether established for conservation or mitigation purposes. On a wetland policy level, this study can be used to present an alternative approach to meeting federal and state wetland ‘no-net-loss’ policies through a combination of large-ratio preservation of existing vernal pool landscapes coupled with site-wide restoration of the small, accumulated damages to the historic wetlands and hydrology. Additionally, continued application of this modeling methodology may be able to contribute to demonstrating significant nexuses between geographically isolated wetlands and traditional navigable waterways. Our novel approach to explicitly modeling changing structural connectivity with limited hydrologic input variables provides the groundwork for greater understanding of the hydrologic connectivity in a modified vernal pool landscape and its restorative potential.

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Appendix I – List of Online Resources

US Army Corps of Engineers
Hydrologic Engineering Center
Hydrologic Engineering Center's River Analyses System (HEC-RAS)
http://www.hec.usace.army.mil/software/hec-ras/

California Department of Water Resources
California Data Exchange Center (CDEC)
UC Merced Weather Station
http://cdec.water.ca.gov/dynamicapp/staMeta?station_id=UCM

California Department of Water Resources
California Irrigation Management Information System (CIMIS)
Station #148 – Merced
https://cimis.water.ca.gov/Stations.aspx

Appendix II – Pond Hydrologic Flux – 15min Data

Supplemental File Upload: *AVO_PondFlux_15min_2018WY.csv*

Joined data table of Avocet Pond hydrologic flux from November 6, 2017 – July 23, 2018

Column	**Description**	**Units**
DateTime	Date and Time for 15min Data	YYYY-DD-MM hh:mm:ss
WSE	Avocet Pond Water Surface Elevation	Meters above sea level (m a.s.l.)
precip_event_mm	15min Precipitation Event from UCM CDEC	mm
precip_acc_mm	Accumulated Precipitation from UCM CDEC	mm
SAm	Pond Surface Area	m
VOLm3	Pond Volume	m3
SAac	Pond Surface Area	acres
VOLacft	Pond Volume	acre-feet

Appendix III – Model Validation Confusion Matrices

Table 6 Model Validation Confusion Matrix: Model Maximum Inundation vs. EIP Wetland layer

		EIP Wetlands		
	Upper Side	Inundated	Not Inundated	
Model	Inundated	42	51	93
	Not Inundated	13	894	907
		55	945	1000
	Lower Side	Inundated	Not Inundated	
Model	Inundated	66	53	119
	Not Inundated	82	799	881
		148	852	1000
	Lower Pond	Inundated	Not Inundated	
Model	Inundated	28	61	89
	Not Inundated	19	892	911
		47	953	1000
	Lower FL	Inundated	Not Inundated	
Model	Inundated	69	157	226
	Not Inundated	75	699	774
		144	856	1000
	Upper Pond	Inundated	Not Inundated	
Model	Inundated	18	46	64
	Not Inundated	12	924	936
		30	970	1000
	Upper FL	Inundated	Not Inundated	
Model	Inundated	86	153	239
	Not Inundated	68	693	761
		154	846	1000
	Model Domain Subbasins	Inundated	Not Inundated	
Model	Inundated	309	521	830
	Not Inundated	269	4901	5170
		578	5422	6000
	Pond	Inundated	Not Inundated	
Model	Inundated	422	33	455
	Not Inundated	106	439	545
		528	472	1000
	Model Domain Full	Inundated	Not Inundated	
Model	Inundated	731	554	1285
	Not Inundated	375	5340	5715
		1106	5894	7000

Table 7 Model Validation Confusion Matrix: Model Maximum Inundation vs. Expected Inundation based on channel observations during March storm runoff surge

		Expected		
	Upper Side	Inundated	Not Inundated	
Model	Inundated	54	39	93
	Not Inundated	114	793	907
		168	832	1000
	Lower Side	Inundated	Not Inundated	
Model	Inundated	70	49	119
	Not Inundated	78	803	881
		148	852	1000
	Lower Pond	Inundated	Not Inundated	
Model	Inundated	53	36	89
	Not Inundated	65	846	911
		118	882	1000
	Lower FL	Inundated	Not Inundated	
Model	Inundated	87	139	226
	Not Inundated	34	740	774
		121	879	1000
	Upper Pond	Inundated	Not Inundated	
Model	Inundated	40	24	64
	Not Inundated	91	845	936
		131	869	1000
	Upper FL	Inundated	Not Inundated	
Model	Inundated	94	145	239
	Not Inundated	31	730	761
		125	875	1000
	Model Domain Subbasins	Inundated	Not Inundated	
Model	Inundated	398	432	830
	Not Inundated	413	4757	5170
		811	5189	6000
	Pond	Inundated	Not Inundated	
Model	Inundated	368	87	455
	Not Inundated	45	500	545
		413	587	1000
	Model Domain Full	Inundated	Not Inundated	
Model	Inundated	766	519	1285
	Not Inundated	458	5257	5715
		1224	5776	7000