Responses to HESS Referee Comments
Fox et al. Manuscript

The authors appreciate the excellent review comments from the Editor and Referees. Our responses to each comment are shown below the comments in italics. Attached is a markup version of the manuscript so the editor and reviewers can see the modifications that have been made. The markup version does not contain any figures. Note that Figures 4 and 5 were combined and a new Figure 6 was added (both were suggestions from reviewers). The only responses included here from Short Comments are those where changes to the manuscript were made. Other responses to Short Comments can be found in the HESSD discussion.

<u>Referee #1</u>

1. Analysis conducted in this paper in terms of long term average annual flows is not sufficient to assess volume requirements on a seasonal basis.

We agree with the reviewer's comment and recognize the importance of characterizing intra-annual variability of natural outflow. Our manuscript recommends that future work be conducted in this area. We have been engaged in modeling work to explore seasonal variability of natural outflow. However, due to the complexity of the subject matter and issues of excessive manuscript length, we determined that this subject would best be addressed in a future separate manuscript.

2. The authors assume the long term average annual ground water flows is unchanged. One condition is for the groundwater catchment to be the same as the surface water catchment. The authors should provide this.

We understand and agree with the reviewer's first statement. However, we do not understand the reviewer's second sentence and seek clarification.

3. With the many assumptions the authors make, the analysis has been reduce to a simple mass balance evaluation (see Fig 6). In effect the flow to the bay is the rim inflows plus precipitation on the catchment valley floor less evaporation/evapotranspiration, and groundwater (and basin imports/transfers). Catchment precipitation is unchanged. Basin imports/transfers are comparatively small to the other components. Therefore the analysis has been reduced to a comparison of evaporation/evapotranspiration of the valley floor catchment cover under various vegetation cover. Calculations are made in terms of long term average annual flows. Under these conditions it is unsurprising that the authors conclude delta outflows are unchanged. The extent of assumptions made and time scale used does not make the analysis useful to addressing the questions posed and the concerns in this watershed.

We agree with the reviewer's characterization of the manuscript's simple mass balance approach. However, we do not share the reviewer's conclusion that our results are "unsurprising". On the contrary, we find the similarities between annual water use under natural and current conditions to be highly counter-intuitive given (1) the extensive landscape *changes that have taken place over the last 160 years and (2) the sizeable out-of-basin transfers that support irrigated agriculture in the San Joaquin Valley and urban development in the San Francisco Bay area, along the central California coast, and in southern California. We anticipate that most readers will find the results to be quite surprising and controversial. As described throughout the manuscript, ecosystem decline in the Bay-Delta has been attributed in part to assumed changes (i.e. human-induced reduction) in the amount of annual Delta outflow – changes that are not supported by our results.*

Furthermore, we disagree with the reviewer's comment that the analysis is not useful for addressing the questions posed. Our analysis provides the first estimate of natural Delta outflow in the San Francisco Bay-Delta estuary, compares this natural outflow estimate with current level outflow, and demonstrates that unimpaired flow calculations significantly overestimate natural outflow and therefore should not be used as a surrogate measure of natural conditions or to set flow standards to restore ecosystem health.

4. The study has been useful and helpful in clarifying and quantifying unimpaired flows and natural Delta outflows.

We thank the reviewer for the positive feedback on the usefulness of the study.

<u>Referee #2</u>
ORIGINAL:

1. It would help if Figure 1 also showed where the flow into the Bay Delta where the "unimpaired flow" standard is being applied.

We agree with the reviewer that the manuscript will be enhanced by identifying the location of Delta outflow on Figure 1. The enhancement was accomplished by adding an inset map of San Francisco Bay and providing an arrow signifying Delta outflow leaving the Delta and entering the Bay and Pacific Ocean. For clarification, unimpaired flow standards are being contemplated but have yet to be applied to the San Francisco Bay-Delta watershed.

2. While the argument is easy to follow, the results could be presented in a clearer manner. The endless tables get tedious. Please include some graphical representation of the three flows under Natural (Case I), Current and Unimpaired. This is the main point of the paper but not presented anywhere.

We agree with the reviewer's comment and we created a new figure (Figure 6) that compares long-term annual outflow under natural, current and unimpaired conditions.

3. It is really striking how different the original and current land use of the region is in Figure 4 and Figure 5 – but it's made difficult to compare because the classification systems are totally different. Would it be possible to use a single classification system for Historical (natural) and Current land use and show them next to each other instead of two separate graphs? If this is not possible, another option would be to show the natural and current ET maps next to each other (using a single legend).

We agree with the reviewer's comment that showing the maps in Figures 4 and 5 next to each other will allow readers to more effectively compare natural and current land use. We replaced Figures 4 and 5 with a single figure (Figure 4) showing the maps side-by-side. Unfortunately, it is not possible to use a single classification system for both maps. Instead, we simplified the legend associated with the current land use map by combining similar classifications.

4. While the analysis is simple – the implications are quite far reaching and therefore it's necessary to be sure that the core components are correct. The argument is contingent whether the base map used (the CSU Chico map) is correct and whether the correct ET values have been chosen for different vegetation types. Would it be possible to provide evidence that the CSU map is consistent with other estimates of land use particularly for the high ET species (wetlands and perennial grasslands)? E.g. a single table in an Appendix with the CSU area compared to area estimates by other scholars for each species.

We agree with the reviewer's observation that our vegetation type and ET assumptions are critical to the analysis. As explained in the discussion manuscript, the CSU Chico map was only the starting point for our work. We used numerous other sources to confirm and modify the Chico map. Our analyses are documented in Fox and Sears (2014), which compares our estimates with those made by others where comparison was feasible. Direct comparison was not always feasible as others either used different geographic boundaries and/or different vegetation classifications. We added the following narrative to the revised manuscript in section 3.4.2:

"The natural vegetation areas estimated using these methods were also compared with those estimated by others. This work estimated about 0.40 million hectares of permanent wetlands. Others have estimated 0.40 (Fox 1987) to 0.53 million hectares (Hilgard 1884, Shelton 1987) for slightly different Valley Floor boundaries. This work estimated about 1.62 million hectares of grasslands. Others have estimated 2.02 (TBI 1998) to 2.18 (Fox, 1987; Shelton 1987) million hectares for slightly different Valley Floor boundaries. The current study estimated approximately 0.77 million hectares of vernal pool habitat in the Valley Floor outside of the floodplain. Others have estimated about 0.97 million hectares of vernal pool habitat (Holland 1978, 1998; Holland and Hollander 2007) for slightly different Valley Floor boundaries. This work also estimated 0.29 million hectares of riparian forest based on CSU Chico's map, which is low compared to estimates by others including 0.35, 0.38, 0.37, 0.58, and 0.65 million hectares estimated by Shelton (1987), Roberts et al. (1977) , Katibah (1984) , Fox (1987), and Warner and Hendrix (1985), respectively, for slightly different Valley Floor boundaries."

Additional Reference added:

Hilgard, E.W., Report on the Physical and Agricultural Features of the State of California, U.S. Census Office, Government Printing Office, Washington, D.C., Tenth Census, v. 6, 649 -796, 1884.

5. Just because annual natural flows are in the range of current flows, it doesn't mean that human alterations have not impacted the delta in terms of the fluctuations and timings of flows. It's possible that humans have either increased or decreased inter-annual and intra-annual variability (will need dam operation data for this). I think presenting monthly analyses as a graph may help – considering that the analysis was actually done at a sub-annual scale.

We agree with the reviewer's comment that human alterations have likely changed the fluctuations and timing of flows relative to natural conditions and recognize the importance of characterizing intra-annual variability of natural outflow. Our manuscript recommends that future work be conducted in this area. We have been engaged in modeling work to explore seasonal variability of natural outflow. However, due to the complexity of the subject matter and issues of excessive manuscript length, we determined that this subject would best be addressed in a future separate manuscript.

6. The effect of GW is clearly important and missing as the authors acknowledge. If GW depletion has occurred should this be considered a net addition of "water supply" into the basin just as inter-basin transfers from the Trinity River are considered inputs?

We agree with the reviewer's comment that groundwater is an important element of the analysis. The analysis assumes that under natural conditions: (1) there is no significant groundwater inflow from the 'rim' watersheds to the valley floor, (2) the groundwater aquifer is approximately coincident with the valley floor, and (3) there is no long-term change in groundwater storage. Changes in groundwater storage must be considered at seasonal and inter-annual time scales to correctly characterize streamflows. At these shorter timescales, groundwater may act alternately as a source and then a sink. At longer time scales, the net gain or net loss in groundwater storage translates into a net loss or net gain in water supply. A long-term reduction in groundwater storage has been included in the historical water balance as a net water supply. However, under the natural condition assumptions, there is no long-term change in groundwater storage and no associated net water supply. We do not propose any changes to the manuscript on this issue but invite suggestions.

7. I am assuming urban uses are considered to be net of return sewage flows – this isn't clearly specified anywhere.

The analysis presented in the manuscript considers the depletion (or consumption) of surface water and groundwater by different land uses. For agriculture and natural landscapes, depletion is equal to evapotranspiration. For urban land use, depletion is assumed equal to a fraction of the outdoor water use. All indoor water use is assumed to be non-consumptive, i.e,. all indoor water use is assumed to return to either surface water or groundwater. We do not propose any changes to the manuscript on this issue but invite suggestions.

8. The paper ends with a call for more research, which is fine but not sure that will help the immediate problem of declining fish. I am reasonably convinced by the author's central argument that "unimpaired flows" are an inappropriate standard to manage the Bay Delta

and “natural flows” are a better standard. However, it is an indisputable fact that species in the Bay Delta are declining. Early on, the authors suggest the causes may lie elsewhere with sedimentation, nutrients, flow timing, temperature changes etc.). Thus, the analysis does not help actually solve the Bay Delta problem and sadly makes it much more complicated. There is a tendency among agencies to fixate on a single parameter because it is so much easier to track and communicate to the public and policy makers – but sometimes it’s simply wrong. It would help sharpen the paper if this point is made more clearly at the end and also offer some alternatives if the objective is to save endangered fish species.

This is an insightful comment by the reviewer. We agree that (1) there is a tendency among agencies to fixate on a single parameter and that (2) this work in isolation will not solve the Bay Delta problem. The authors refrained from discussion of other potential ecological stressors in this manuscript to focus on the hypothesized Delta outflow stressor. We believe that our criticism of the literature on the outflow stressor and the results of this focused study will be quite controversial. If we were to dilute the focus of this paper through examination (and possible criticism) of other potential stressors, we believe such a change would invite undue controversy and detract from the main point of the study.

SECOND RESPONSE:
Received and published: 31 May 2015

1. On reading the author response I figured out what is bothering me: The authors are comparing observed current flows to modeled "natural flows". [1] Natural flows are a counter factual scenario created by modelling the recent rainfall record but using historical land use scenarios. At present, as I see it, the model is an unvalidated one. I had assumed somewhere that if the same ET modelling approach were applied to current land uses it would reproduce current flows within reasonable bounds - hence my questions about urban return flows and groundwater depletion. Now I realize this wasn’t actually done. But without this step, the model remains unvalidated.

The paper does not compare observed current flows with modeled natural flows. The metric of interest, Delta outflow, is reported at the mouth of a tidally influenced estuary where direct measurement of flows is not feasible. Measured Delta outflow data for the period 1922 to 2009 do not exist, although Delta inflows are measured and tidally-averaged Delta outflows, referred to as the Net Delta Outflow Index or NDOI, have been computed by others using a similar mass balance approach. See: http://www.water.ca.gov/dayflow/. We are comparing two sets of hypothetical flows to determine the impact on Delta outflow of changes in land use. Both sets assume a fixed land use over an 88-year period, and a repeat of the historical climate (i.e., precipitation and temperature). The first set of flows uses the ‘existing’ (2011) land use, the second set of flows uses pre-development land use.

2. I think the authors should do this given the controversial claims of the paper. This should be possible to do this with the data available. Simply put - use the exact same approach to current land uses, show that it replicates current flows and then compare ET today to ET in the natural scenario. [2]

While we understand the sentiment of wanting to validate a model, we are not "modeling" either natural flows or current flows as they existed at any point in time. Rather, we are comparing two sets of hypothetical flows under varying land use conditions with constant climate to evaluate the impact of land use changes on Delta outflow. Others have used a similar mass balance approach to estimate actual Delta outflows, referred to as the NDOI.

3. Because the numbers are not communicated clearly, it is difficult to track the pieces. E.g. the paper states that of the 52 billion m3/year of water available (including _2 billion m3/year of inter-basin imports and GW depletion) about 32 billion m3/year is used by humans and 20 billion m3/year is outflow to the delta. What I don't understand is how come ET from natural landscapes is currently zero? Does the 32 billion m3/year include native vegetation or is that truly negligible? Is the amount of water consumed for " irrigation, municipal, industrial, and other uses" 32 billion m3/year (Line 14) or 26 billion m3/year (Line 26) on Page 3865 [P16, L24]? Or is the difference between the two ET from current natural vegetation?

The 26.0 billion m^3/year cited in this comment is a typographical error, also noted by Referee #3, Comment 9. The amount of water consumed by irrigation, municipal, industrial, and other uses is the same in both cases or 31.9 million m^3/year. This typographical error will be corrected, i.e., 26.0 billion m^3/yr will be changed to 31.9 billion m^3/yr. We combined Figures 4 and 5 so that current land use and natural land use could be compared side by side to clarify the fact that development has resulted in removing nearly all of the natural vegetation.

4. Clear visualization of the break-up of water balance in the three scenarios (current, unimpaired and natural) is critical to making the case to the scientific community and ultimately policy makers. E.g. Pie charts of the 2011 water balance or stacked bar charts over time comparing the water balance components under current, unimpaired and natural scenarios would be helpful. [4]

Response: "Unimpaired" is not a land-use based scenario. It is derived from an incorrect assumption by others that depletion of water on the Valley Floor is approximately balanced by precipitation on the Valley Floor. A bar chart was added to the manuscript as suggested by this and another reviewer (Figure 6).

<u>Referee #3</u>

1. P3855, L22_23 [P9, L22]: The authors mentioned the effect of land use and forest management changes on the rim inflows. This effect is not considered in this study as explained in P3856, L3_6. If the water use in the Valley Floor is not the reason for the Delta outflow decline, then the rim inflows change might be the possible cause, assuming no significant changes in precipitation in the last 100 years. So it would be interesting to see the difference in rim inflows under "natural" condition and current condition.

The analysis suggests that Delta outflows under natural conditions were approximately equal to current Delta outflows, when controlled for climate. Therefore, Delta outflows have not declined, *at least not to the extent suggested by previous research. The authors agree that changes in historical land use in the upper watersheds have impacted stream flows. However, these land use changes, which include changes in forest management, are much less dramatic than the clearance of natural vegetation from the valley floor. Consideration of how upper watershed land use changes have affected stream flows is important to understanding natural flows, but it is outside the scope of the present study.*

2. A validation on the evapotranspiration estimation based on vegetation distribution would be helpful. The authors may compare the estimation results with the observed evapotranspiration in some other locations with similar vegetation distribution to see if they agree with each other.

Validation of the evapotranspiration estimates can be found in Howes et al. (2015). In that work, the authors based evapotranspiration estimates on vegetation coefficients (Kv's) developed from actual evapotranspiration measurements for those vegetation types. The actual evapotranspiration was estimated using monthly Kv's and monthly grass reference evapotranspiration (locally measured). In the cases where vegetation evapotranspiration was rainfall dependent (such as rainfed grasslands and chaparral), the actual evapotranspiration was developed on a daily basis using a calibrated soil water balance model. Calibration of this model was based on measured evapotranspiration for those vegetation types. Finally, Howes et al. (2015) compared the estimated evapotranspiration for wetlands and riparian habitat to measured evapotranspiration using a surface energy balance with remote sensing data showing excellent agreement. Since this work is referenced in the manuscript, we do not propose any changes.

3. P3863, L5_6 [P17, L7]: "in Cases V and VI, the mix of rainfed perennial grasslands was varied based on the volume of rim inflow to the Sacramento and San Joaquin basins." Could the authors explain more about this relationship and how you determine the vegetation distribution in Cases V and VI based on this relationship?

We added the following narratives to the revised manuscript in section 3.4.3:

"Vegetation areas in Case V are identical to Case I, except grassland areas not classified as vernal pools are assumed to be a mix of rainfed and perennial grasslands that vary from year to year based on the annual runoff volume as measured by the Eight River Index (CDWR 2013). Grassland areas are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and the driest year."

"Vegetation areas in Case VI are identical to Case I, except vernal pools are assumed to be a mix of rainfed and perennial grassland. Aggregate grasslands are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and the driest year."

4. Could the authors discuss the results in Table 5?

Results of the sensitivity analysis are summarized in Table 5. The discussion of results currently in the manuscript was expanded in Section 4.

5. P3867, L16_19 [P21, L18]: This statement is a little bit confusing, especially the part: "the unimpaired outflow calculation assumes that water use upstream of the Delta is limited to only Valley Floor precipitation."

Manuscript language was revised to more clearly describe CDWR's unimpaired flow calculation in Section 5.

6. The abstract is a little bit too long.

The abstract was modified to reduce its overall word count.

7. The term ETo is defined as potential evapotranspiration (P3857, L20 [P11, L20]) and as grass reference evapotranspiration (P3858, L5 [P12, L25]). Maybe choose one.

We replaced potential evapotranspiration with grass reference evapotranspiration in the manuscript.

8. P3861, L1 [P15, L1]: change "sensitively analysis" to "sensitivity analysis"; change "uncertainity" to "uncertainty".

The typographical errors identified by the reviewer were corrected.

9. P3865, L24 [P19, L24]: the current water use level should be 31.9 billion m3/yr, as mentioned in P3865, L13 [P19, L13].

The typographical error identified by the reviewer was corrected, i.e. 26.0 billion m3/yr will be changed to 31.9 billion m3/yr.

<u>Referee #4</u>

1. There is vagueness in the context about to what degree this underestimation of the natural vegetation uses can impact the calculation of the "natural" Delta outflow. In Sect. 3, there are some explanation about the data sources that may underestimated some vegetation types. The "CSU Chico" study is the key about the fundamental information of the natural vegetation configuration. An original figure of vegetation covers from this study and comparing it with Fig. 4 can be helpful. And also, because that the CSU Chico study might be a main source of the underestimation of some types of vegetation covers, I think it is important to know is there any information in those sources and maps that can help to ensure the errors to be indifferent. It is noticed that in page 3866 [P20], the last paragraph of Sect. 4, the authors briefly discussed about the assumptions. I believe this part can be improved if the authors can give a more detailed analysis.

See our response to Referee #2's Comment 4. The CSU Chico map was only the starting point for our work. We used numerous other sources to confirm and modify the Chico map. Our analyses are documented in Fox and Sears 2014. Comparisons of our natural vegetation land area estimates with those made by others indicate that our estimates result in evapotranspiration on the lower end of the range. When faced with a choice, we intentionally made land use assumptions that underestimate evapotranspiration in an effort to assure that natural Delta outflows were not underestimated in our base case (Case I). We then varied our vegetation land use assumptions in sensitivity Cases II – VIII to explore the effect of land use assumptions on natural Delta outflow. Modification have been made in Section 3.4.2 to summarize the comparison of our base case vegetation land areas with those made by others and explain their impact on our resulting estimates of Delta outflow.

2. Abstract – p.3849 Line 7 [P3, L7-8]: Confused statement. This paper is arguing that the annual average Delta outflow is not decreasing due to development. Thus the reduction in annual average Delta outflow does not exist and should be excluded from the causes of the ecosystem declines, according to this study.

The sentence in the abstract was rephrased as follows: "Thus it is unlikely that observed declines in native freshwater aquatic species are the result of annual average Delta outflow reductions."

3. Sect. 3.2 – p. 3854 Line 23---27 [P8, L24-28]: Dubious. Is that true that the long---term groundwater storage did not changed significantly? The massive replacement of natural vegetation cover by artificial landscapes usually changed the surface infiltration and thus may resulted in declining groundwater level. This simplification may lead to ignorance of the most important factors that may contribute to the reduction of the Delta outflow. Please give some measures or data about the historical groundwater table variation to clarify that this point.

We agree with the reviewer that replacement of natural vegetation with artificial landscape has changed surface infiltration and other factors that have impacted groundwater levels. Certainly groundwater levels are lower under current conditions relative to natural conditions. However, the statement on p. 3854 [P8] *relates only to the steady state assumption associated with Equation 1 under natural conditions. We agree that modification of the landscape changed surface infiltration and other factors that have affected the groundwater table under current conditions. Our analysis assumes that, under natural conditions, groundwater conditions are at dynamic steady state, i.e. no long-term gains or losses in groundwater storage are experienced over the 88-year period of record. No changes to the text are proposed.*

4. Sect. 3.4.3 – p.3862 Line 12 [P16, L12]: Why case 4 is necessary? Why there isn't a case that it is rainfed grassland in Sacramento and Delta Basins and mix of perennial grassland and vernal pools in San Joaquin Basin?

The annual water budgets produced by our analysis suggested that water supply in the San Joaquin Basin may have been insufficient to support Case III vegetation. As a remedy, the landscape assumption was modified in Case IV. Additional text was added to justify the need for Case I in section 3.4.3.

5. Sect. 3.4.3 – p. 3863 Line 15---24 [P17, L12-24]: Is the grasslands in Case 7 and 8 are constant or variable? Are they used to compare with Case 1 and 4? This should be clearly stated and may be important. If this is it, why not add more cases to compare with case 5 and 6 to explore impact of the foothill hardwoods and wetland at individual years level? Aren't the case 5 and 6 are more closely represent the natural conditions?

As the reviewer correctly points out, we believe Cases V and VI most closely represent the natural landscape. And as the reviewer suggests, many sensitivity scenarios could be explored and reported. We believe that the eight scenarios that we show are all reasonable scenarios, and while providing additional scenarios would be interesting, the presentation and discussion of additional scenarios would become unwieldy. Regarding Cases VII and VIII, (1) the grassland assumptions are identical to Case I, i.e. they are constant and (2) the purpose of these cases was to explore sensitivity of the Case I hardwood assumption. No change to the text is proposed.

6. Sect. 3.4.3 – p. 3864 Line 1---4 [P18, L1-4]: Same question as 3. Why specifically wetlands in San Joaquin Basin are assumed as rainfed grasslands as case 8. Why no case 9 that Sacramento and Delta basins with rainfed grasslands? I am not very familiar with the study areas, what's the difference between these two regions that makes the authors focused just on changing settings in San Joaquin Basin?

As the reviewer points out, this comment is similar to that raised regarding Case IV. The motivation for considering both scenarios is similar – the San Joaquin Basin has a smaller water supply available to it relative to the Sacramento Basin and the Delta. We agree with the reviewer and clarifying text was added to section 3.4.3 to justify the special attention provided to the San Joaquin Basin.

7. Sect. 4 – p. 3864 Line 23 [P18, L23]: I did not find the numbers of 29.6 and 30.8 in Tab. 5. It seems according to Tab. 5, the total water use are respectively 30.4 and 29.7 billion m3yr---1 for case 5 and 6. And excluded the aquatic surface, the natural water use in this two cases should be 30.1 and 29.4 billion m3yr---1. It this a mistake? BTW, I notice that the sum of water use by grassland--- vernal pool and wetlands is 74%(40%+34%) of the supply, that these natural vegetation types are classified as independent types in Tab. 3. I wonder why it is larger than the total water use, which is 60% of the supply.

The total water use numbers will be changed to 30.4 and 29.9 billion m3yr for Cases V and VI as correctly identified by the reviewer. Also, the percentages reported in the text and noted by the reviewer are misleading. Clarification was made that the percentages are of natural vegetation water use NOT total water supply. The percentages now add to 100% of natural vegetation water use. The intent of the text was to provide an approximate breakdown of the water use.

8. Sect. 6 – p. 3869 Line 13---14 [P18, L1-4]: Same as 1. If the annual average freshwater outflow reduced, it still may be cause of the ecosystem declines.

The sentence was rephrased as follows: "Thus it is unlikely that observed declines in native freshwater aquatic species are the result of annual average Delta outflow reductions."

Changes made in Response to Comment from Hwaseong Jin

1. The ET to Precipitation based on their precipitation estimate (15.9) and the Delta Outflow (about 20 based on their Cases V and VI) in the Valley Floor would be 1.89. , which is extremely high perhaps unnatural. Sanford and Selnick (2013) presented a map of ET/P ratios of the Conterminous US, which has the max value at 1.29 (in range of 1.2-1.29). Authors should discuss about whether their ET/P ratio falls within any known estimates. If the potential mas ET/P value of 1.2 were applied to this study, the outflow would be larger than 31 billion m^3/yr, which would be close to the unimpaired outflow of 35 billion m^3/yr.

The following text was added to Section 4 of the manuscript to clarify the misunderstanding: "The resulting evapotranspiration-to-precipitation (ET/P) ratios, 0.54 to 0.72 are estimated as total water use from Table 5 divided by the sum of Valley Floor precipitation (15.9 billion m^3/yr) and rim inflows (34.2 billion m^3/yr), and are consistent with ET/P ratios reported by others (Sanford and Selnick, 2013). The Valley Floor vegetation described in this work was not sustained by precipitation falling on the Valley Floor. The Valley Floor also used large quantities of runoff from surrounding watersheds that was not consumed in those watersheds but was made available for consumptive use through the seasonal flooding cycle. Therefore, rim inflows effectively act as precipitation to the Valley Floor"

Changes made in Response to Herbold Comment #5

5. Original comment: In both their introduction and conclusions they claim that outflow as the only thing that has been addressed in environmental protection. They overlook the $2 Billion work Sac Regional Sanitation District has been required to undertake; work which Stockton earlier undertook because their sewage is inseparable from their drinking water intake. Similarly, the drinking water requirement at the intake for Contra Costa Water District has long been the most frequent control of outflow. The authors also overlook the 8000 acres of habitat restoration in the Biological Opinion for Delta Smelt, and the 60000 acres proposed in the Bay Delta Conservation Plan. These are legal requirements that directly address the ecological needs of the species they cite and are major investments independent of flow. Their statements to the contrary are incorrect.

It was not the intent of the authors to suggest that current environmental protections in the Bay-Delta watershed have been limited to flow measures. We reviewed the manuscript and removed this language in the introduction and conclusion.

MARKUP VERSION

Reconstructing the Natural Hydrology of the San Francisco Bay-Delta Watershed

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Abstract

~~The San Francisco Estuary, composed of San Francisco Bay and the Sacramento-San Joaquin River Delta, is the largest estuary along the Pacific coast of the United States. The tributary watersheds of California's Central Valley are the principal sources of freshwater flow into the San Francisco Bay-Delta estuary. The Delta serves as one of the principal hubs of California's water system, which delivers 45 percent of the water used statewide to 25 million residents and 16,000 km^2 of farmland.~~

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~~The development of California, from small-scale human settlements that co-existed with an environment rich in native vegetation to the eighth largest economy in the world was facilitated by reconfiguring the state's water resources to serve new uses: agriculture, industry, and a burgeoning population. The redistribution of water from native vegetation to other uses was accompanied by significant declines in native aquatic species that rely on the San Francisco Bay-Delta system. These declines have been attributed to a variety of causes, including reduction in~~

~~the amount of freshwater reaching the San Francisco Bay-Delta watershed (Delta outflow); decreased sediment loads; increased nutrient loads; changes in nutrient stoichiometry; contaminants; introduced species; habitat degradation and loss; and shifts in the ocean-atmosphere system, among others. Among these stressors, only the volume of Delta outflow has been regulated in an effort to address the decline in aquatic species.~~

~~As native species evolved under natural landscape conditions, prior to European settlement in the mid-18th century,~~ W~~w~~e evaluated the impact of landscape changes on the amount of Delta outflow reaching San Francisco Bay. ~~We reconstructed the~~ The natural landscape was reconstructed and ~~used~~ water balances were used to estimate the long-term annual average Delta outflow that would have occurred under natural landscape conditions if the climate from 1922 to 2009 were to repeat. These outflows are referred to as "natural" Delta outflows and are the first published~~reported~~ estimate of natural Delta outflow. ~~We then compared t~~These "natural" Delta outflows were then compared with current Delta outflows for the same climate and ~~the~~ existing landscape, including its re-engineered system of reservoirs, canals, aqueducts and pumping plants.

This analysis shows that the long-term, annual average Delta outflow under natural landscape conditions is equal to current Delta outflow because the amount of water currently used by farms, cities, and others is about equal to the amount of water formerly used by native vegetation. The development of water resources in California's Central Valley transferred water formerly used by native vegetation to new beneficial uses without reducing the long-term annual average supply to the San Francisco Bay-Delta estuary. Thus, it is unlikely that observed declines in native freshwater aquatic species are the result of annual average Delta outflow reductions~~Thus, it is unlikely that reductions in annual average Delta outflow have caused the decline in native freshwater aquatic species~~.

1 Introduction

The San Francisco Estuary, composed of San Francisco Bay and the Sacramento-San Joaquin River Delta, is the largest estuary along the Pacific coast of the United States and the home to a rich ecosystem. ~~The tributary watersheds of California's Central Valley are the principal sources of freshwater flow into the San Francisco Bay-Delta estuary.~~ The Delta serves as one of the

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principal hubs of California's water system, which delivers 45 percent of the water used statewide to 25 million residents and 16,000 km^2 of farmland.

The development of California, from small-scale human settlements that co-existed with an environment rich in native vegetation to the eighth largest economy in the world was facilitated by reconfiguring the state's water resources to serve new uses: agriculture, industry, and a burgeoning population. The redistribution of water from native vegetation to other uses was accompanied by significant declines in native aquatic species that rely on the San Francisco Bay-Delta system. These declines have been attributed to a variety of causes, including reduction in the amount of freshwater reaching the San Francisco Bay-Delta watershed (Delta outflow); decreased sediment loads; increased nutrient loads; changes in nutrient stoichiometry; contaminants; introduced species; habitat degradation and loss; and shifts in the ocean-atmosphere system, among others. Among these stressors, only the volume of Delta outflow has been regulated in an effort to address the decline in aquatic species.

1 As native species evolved under natural landscape conditions, prior to European settlement in the mid-18th century,

The Central Valley of California is a 60 to 100 km wide broad flat alluvial plain, stretching over 750 km from north to south and covering about 58,000 km^2 (containing the irrigated land from south of Redding to south of Bakersfield in Figure 1). This valley is entirely surrounded by mountains except for a narrow gap on its western edge through which the combined Sacramento and San Joaquin Rivers flow to the Pacific Ocean through San Francisco Bay (Figure 1). This valley is the agricultural heartland of the United States, producing over 360 products and more than half of the country's vegetables, fruits and nuts. It is often considered the most productive agricultural region in the world, a status achieved by significantly re-engineering the natural landscape.

The tributary watersheds in the northern portion of the Central Valley, referred to in this work as the Valley Floor (Figure 2), areis the major sources of freshwater to the San Francisco Bay-Delta system, the largest estuary along the Pacific coast of North America and the home to a rich ecosystem. It is also the major source of freshwater that sustains most of the agricultural production and population of California. The Sacramento River from the north and the San Joaquin River from the south flow toward each other, joining in the Delta. These rivers are the

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~~principal freshwater supply for the San Francisco Bay-Delta system as well as 45 percent of the water used statewide by 25 million residents and 16,000 km^2 of farmland.~~

The development of California from small-scale human settlements that co-existed with an environment rich in native vegetation to the eighth largest economy in the world was facilitated by reconfiguring the state's water resources to serve new uses: agriculture, industry, and a burgeoning population. The redistribution of water from native vegetation to other uses was accompanied by significant declines in native aquatic species that rely on the San Francisco Bay-Delta system. Declines in native aquatic species have been documented in the San Francisco Bay-Delta system over the last several decades (Jassby et al., 1995; MacNally et al., 2010; Thomson et al., 2010). Many aquatic species have been classified as endangered, threatened, and species of concern, e.g., Sacramento River winter-run Chinook salmon, Delta smelt, Sacramento Splittail, Longfin smelt, Southern green sturgeon (Lund et al., 2007). These declines have been attributed to several factors including reduced volume and altered timing of freshwater flows from the tributary watersheds (Delta outflow); decreased sediment loads; increased nutrient loads; changes in nutrient stoichiometry; contaminants; introduced species; habitat degradation and loss; and shifts in the ocean-atmosphere system (Luoma and Nichols, 1993; Jassby et al., 1995; Bennett and Moyle, 1996; MacNally et al., 2010; Glibert, 2010; Glibert et al., 2011; Miller et al., 2012; Cloern and Jassby, 2012).

~~However, among these, only Delta outflow has been directly or indirectly regulated in an effort to stem the decline in aquatic species as it is generally believed that reduced outflows are directly related to reduced species abundance. This study investigates whether the volume of freshwater flow reaching the San Francisco Bay-Delta system has been reduced by development within the tributary watershed and thus is a contributing factor to species declines.~~

The native species of concern evolved and thrived under natural landscape conditions, or those that existed prior to European settlement starting in the mid-18th century. These undisturbed conditions are referred to in this work as "natural" conditions, meaning undisturbed by western civilization. Thus, "natural" Delta outflows are those that would have occurred with "natural" landscape conditions.

The natural landscape included immense inland marshes located in natural flood basins along major rivers (Alexander et al., 1874; Hall, 1887; Garone, 2011), lush riparian forests on river levees (Katibah, 1984), and vast swaths of grasslands interwoven with vernal pools and immense valley oaks in park-like savannas that extended from the floodplains to the oak- and pine-covered foothills (Holland, 1978; Burcham, 1957; Dutzi, 1978). This landscape was fed by periodic overflows of the rivers into natural flood basins along the major rivers. Figure 3 is an idealized cross-section through the Valley Floor that illustrates the major features of this natural landscape.

This landscape was dramatically altered, starting in the mid-18th century, to support new land and water uses. The native vegetation was largely replaced by cultivated crops, the flood basins were drained, the rivers were confined between levees, headwater reservoirs were built to store floodwaters, and an extensive system of canals and aqueducts was built to move water from its point of origin to distant locations. ~~In this study, we estimate long-term annual average Delta outflow under natural landscape conditions (referred to as "natural" Delta outflow) using a water balance. We then compare natural Delta outflow with Delta outflow under current conditions for the same climatic conditions. This is the first published estimate of natural Delta outflow into the San Francisco Bay-Delta estuary.~~

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In this study, the hypothesis that current annual average freshwater flows are lower than natural annual average flows into the estuary is tested using a simple water balance, normalized to the contemporary climate. We then compare our natural Delta outflow estimate with an estimate of Delta outflow that occurs annually under current conditions. This is the first published estimate of natural Delta outflow into the San Francisco Bay-Delta estuary. Others have used a surrogate, known as "unimpaired" flows in California, to estimate natural outflows. As will be demonstrated, the surrogate fails to account for evapotranspiration by native vegetation, the major consumptive use of water in the natural system, resulting in a significant overestimate of natural Delta outflows.

2 Study Area Background

Prior to development, starting in the mid-18th century, the channels of the major rivers did not have adequate capacity to carry normal winter rainfall runoff and spring snowmelt (Grunsky, 1929; CA State Engineer, 1908). The rivers overflowed their banks into vast natural flood basins flanking both sides of the Sacramento and San Joaquin Rivers (Hall, 1880; Grunsky, 1929). Sediment deposited as the rivers spread out over the floodplain and built up natural levees along the river channels~~ (Figure 3)~~. These natural levees were much larger and more developed along the Sacramento River than along the San Joaquin River (Hall, 1880).

The natural levees were lined with lush riparian forest. The floodplains contained large expanses of tule marsh, seasonal wetlands, vernal pools, grasslands, lakes, sloughs and other landforms that slowed the passage of flood waters (Whipple et al., 2012; Garone, 2011; Holmes and Eckmann, 1912)~~ (Figure 4)~~. Groundwater generally moved from recharge areas along the sides of the valley towards topographically lower areas in the central part of the valley, where it was depleted through marsh, vernal pool, and riparian forest evapotranspiration (TBI, 1998; Bertoldi et al., 1991; Williamson et al., 1989; Davis et al., 1959).

Grasslands interspersed with vernal pools (seasonal wetlands) stretched from the edge of the floodplain to the foothills, generally overlying relatively impermeable hardpans and claypans that supported perched water tables. This habitat once occupied nearly all level lands between the foothills and floodplain and was the dominant vegetation under natural conditions, supplied by perched aquifers, overland runoff from the foothills, and precipitation~~ (Figure 4)~~.

This natural landscape, summarized in Figure 4, was radically modified, starting in the mid-18th century, to make it suitable for agricultural (Smith and Verrill, 1998) and urban uses~~ (Figure 5)~~, creating the world's largest water system supporting the eighth largest economy in the world. The native vegetation was removed, river channels were dredged and rip-rapped, levees were raised, the flood basins were drained, bypasses were installed to route flood waters directly into the Delta, and head-stream reservoirs were built to replace side-stream storage, provide protection from floods, and generate electricity. Massive hydraulic works were built to move water from areas of relative abundance to areas of relative scarcity~~,~~ throughout the state, including to Los Angeles and the San Francisco Bay Area. ~~The heart of this system is the tributary watersheds of the Valley Floor in the Central Valley of California (Figures 1 and 2).~~ The history of these changes have been documented elsewhere (Kelley, 1959; Bain et al., 1966; Kahrl, 1979; Thompson, 1957; Kelley, 1989; Hundley, 2001; Olmstead and Rhode, 2004; CDWR, 2013b).

3 Methods

Annual average Delta outflow was estimated under natural landscape conditions (natural Delta outflow) using a conventional water balance. The results of this calculation are compared with

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two estimates of Delta outflow by the California Department of Water Resources (CDWR): (1) current Delta outflow (CDWR, 2012) and (2) unimpaired Delta outflow (CDWR, 2007).

"Unimpaired" outflows are rim inflows from the surrounding mountain ranges, modified or "unimpaired" to remove impacts of upstream alterations that are routed through the existing system of channels and bypasses into the Delta (Figure 2), without any losses or modifications on the way and with no recognition of the natural landscape (CDWR, 2007). These "unimpaired" outflows are frequently misused as a surrogate for "natural" Delta outflow (Cloern and Jassby, 2012, Dynesius and Nilsson, 1994). All three of these estimates are based on the level-of-development methodology and the climate over the period 1922 to 2009 to facilitate direct comparisons.

3.1 Level of Development Methodology

These three estimates of Delta outflow – natural, current and unimpaired – were estimated using a synthetic multi-year hydrologic sequence utilizing a "level of development" approach (Draper et al., 2004). This method routes the same amount of water (rim inflows plus precipitation) over a defined historical period assuming "frozen" conditions such as land use, flood control and water supply facility operations, and environmental regulations. In other words, this method simulates river flows under a repeat of historical climate, but holding land use and facility operations constant.

A historical hydrologic sequence may be generated to represent development as it existed in a particular year (i.e., "1990 level of development"), as it exists today (i.e., "current level of development"), or as it may exist under a projected scenario (i.e., "future level of development"). This approach allows us to estimate the impact of anthropogenic changes on natural Delta outflow by comparing a "natural" level of development with a "current" level of development.

Thus, our estimate of natural outflow is not an estimate of actual flows that occurred under Paleolithic or more recent conditions prior to European settlement (Ingram et al., 1996; Malamud-Roam et al., 2006; Meko et al., 2001). Rather, our natural Delta outflow calculation is an estimate that assumes the contemporary precipitation and inflow pattern to the Valley Floor with the Valley Floor in a natural or undeveloped state, i.e., before flood control facilities, levees, land reclamation, irrigation projects, imports, etc.

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Natural outflow calculations were performed on a monthly basis assuming long-term climatic conditions observed over an 88-year period (1922 to 2009). The calculations assume a conventional California October through September water year. Water balances were calculated around the portion of the Central Valley that drains into San Francisco Bay (referred to as the "Valley Floor") as shown in Figure 2.

3.2 Natural Delta Outflow

Natural Delta outflow was calculated using a conventional water balance as the difference between water supply and water use:

Natural Delta Outflow = Water Supply - Water Use (1)

"Natural" Delta outflows are the outflows that would result if the climate for the period 1922 to 2009 were to occur under "natural" landscape conditions. "Natural" landscape conditions are those that existed prior to the advent of European settlement, starting in the mid-18th century, including native vegetation (Figure 4) and natural landforms such as stream-side flood basins and low levees.

The water supply is the sum of rim inflows from the surrounding mountain ranges into the Valley Floor plus precipitation on the Valley Floor, adjusted to remove impairments such as diversions. The only losses of water under natural conditions were evaporation from water surfaces and evapotranspiration by native vegetation. Water that is not evaporated or evapotranspired flows out of the Delta into San Francisco Bay and is referred to here as "Delta outflow."

Eq. (1) assumes that the long-term, annual average change in groundwater storage would have been zero under pre-development conditions. This assumption would not significantly affect long-term annual average calculations as the year-to-year fluctuations of groundwater exchanges are insignificant compared to average surface water flows. However, it would affect seasonal flow patterns, which is the subject of ongoing work. Net groundwater depletions under pre-development conditions are approximately zero and unimportant to the overall annual water balance (Gleick, 1987).

Water balances are reported for three hydrologic regions that comprise the Valley Floor: the Sacramento Basin, the San Joaquin Basin, and the Delta (Figure 2). Water balances were calculated at a finer resolution for sixteen subsets of the Valley Floor, referred to as "planning areas" (CDWR, 2005a, 2005b) shown on Figure 2.

The results of these conventional water balance calculations are compared with current Delta outflow (CDWR, 2012) and a surrogate for natural outflow, unimpaired outflow (CDWR, 2007), estimated based on the level-of-development methodology.

3.3 Natural Water Supply

The water supply used in the natural water balances was estimated as the sum of rim inflows around the periphery of the Valley Floor plus precipitation that falls on the Valley Floor. The long-term annual average natural water supply is 50.1 billion m^3/yr, comprising 34.2 billion m^3/yr from rim inflows and 15.9 billion m^3/yr from precipitation over the Valley Floor.

The Valley Floor boundary is defined by the drainage basins of the gages used to determine valley rim inflows, adjusted (i.e., “unimpaired”) to remove the effects of upstream storage regulation, imports and exports. Rim inflows are defined as the natural water supply from the surrounding mountains and other watersheds to the Valley Floor. The rim inflows were compiled for undeveloped and developed watersheds from several sources that cover different portions of the study area.

Rim inflows have been affected by changes in land use and forest management and by loss of natural meadows. Agricultural and urban development represents a relatively small portion (about five percent) of the rim watersheds. While low elevation hardwoods and chaparral have been lost and annual grassland areas have increased (Thorne et al., 2008), much of the rim watersheds remain characterized by conifer forest. Forest management practices, which have resulted in denser forest stands compared to pre-development conditions, may significantly affect runoff timing and volume (Bales et al., 2011; CDWR, 2013b). Denser forest canopy prevents snow from reaching the ground and leads to greater evapotranspiration and earlier snowmelt (CDWR, 2013b). However, scientific evidence necessary to quantify relationships between forest management and water supply has been inconclusive. Therefore, our work assumes natural inflows from the rim watersheds are equal to historical inflows adjusted to remove the effects of upstream storage regulation, imports and exports (i.e., unimpaired inflows).

Historical flow records were generated from U.S. Geological Survey (USGS) and California Department of Water Resources (CDWR) gage data and extended through linear correlation with gaged flows in nearby watersheds. Rim inflows from ungaged watersheds were estimated from adjacent gaged watersheds based on relative drainage area and average annual precipitation.

Unimpaired flows (CDWR, 2013a) from developed rim watersheds in the Sacramento and San Joaquin hydrologic regions were assumed to equal natural inflows. Similarly, unimpaired flows from the rim watershed south of the Valley Floor (i.e., the Tulare Lake hydrologic region) were assumed to be equal to natural inflows (CDWR, 2012). Minimal groundwater flow from the Sierra Nevada and Coastal Range to the Valley Floor is assumed, due to the presence of bedrock and high surface slopes (Armstrong and Stidd, 1967; Gleick, 1987; Williamson et al., 1989).

In addition to rim inflows from surrounding mountain watersheds, precipitation falling directly on the Valley Floor contributes to the water supply. Precipitation was calculated for each planning area within the Valley Floor using distributed grids obtained from the PRISM Climate Group at Oregon State University (Daly et al., 2000; Daly and Bryant, 2013; PRISM Climate Group, 2013).

3.4 Natural Water Use

The pre-development Valley Floor was a diverse ecosystem of immense inland marshes, lush riparian forests, and vast swaths of grasslands interwoven with vernal pools and immense valley oaks in park-like savannas that extended from the floodplains to the oak- and pine-covered foothills (Bryan, 1923; Davis et al., 1959; Thompson, 1961, 1977; Roberts et al., 1977; Dutzi, 1978; Warner and Hendrix, 1985; TBI, 1998; Cunningham, 2010; Garone, 2011; Whipple et al., 2012).

Under natural conditions, the only water use was evapotranspiration by natural vegetation and evaporation from water surfaces such as lakes, rivers, and sloughs. We estimated the amount of water used by natural vegetation from the areal extent and evapotranspiration rate for each type of vegetation. We also estimated evaporation from lakes, rivers, and sloughs based on the area and evaporation rates from these bodies of water.

Estimating the water used by natural vegetation (ET) requires information on the vegetation evapotranspiration rate (ET_v) and the areal extent of vegetation (A_v). The volume of water used

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by natural vegetation is then estimated in Eq. (2) as the product of ET_v and A_v summed over all planning areas i and vegetation types j:

$$ET = \sum_{i,j}(ET_v \times A_v) \quad (2)$$

The same method was applied to evapotranspiration from free water surfaces such as lakes, ponds, sloughs, and river channels. The remainder of the section discusses how ET_v and A_v were estimated.

3.4.1 Evapotranspiration

The reference crop method was used to estimate evapotranspiration by natural vegetation (Howes and Pasquet, 2013; Howes et al., 2015). As shown in Eq. (3), the evapotranspiration rate is related to the grass reference~~potential~~ evapotranspiration (ET_o) for a standardized grass reference crop grown under idealized conditions multiplied by a vegetation coefficient (K_v) that accounts for canopy/plant characteristics:

$$ET_v = ET_o \times K_v \quad (3)$$

Two methods were used to estimate K_v, depending upon the available water supply used by various vegetation categories. The methods used to develop the K_v and ET_v used in this study are discussed in detail in Howes et al., (2015). The methods are briefly summarized in the following paragraphs.

For non-stressed vegetation with a continuous water supply throughout the growing season, K_v was estimated from published studies of actual monthly (or more frequent) ET_v using a grass reference evapotranspiration (ET_o) (Howes et al., 2015). The ET_o used to derive the K_v values for this study was computed using the Standardized Penman-Monteith equation (Allen et al., 2005) when a full set of meteorological data was available; otherwise, the Hargreaves equation was used. The accuracy of this method was confirmed for permanent wetlands and riparian forest using actual evapotranspiration measured using remote sensing at two sites in central California (Howes et al., 2015).

For vegetation depending solely on precipitation (chaparral and a portion of the grasslands and valley/foothill hardwood), a daily soil water balance using the dual-crop coefficient method (Allen et al., 1998) was used to estimate ET_v and K_v over the 88-year study period (Howes et al.,

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2015). The ET_v values directly from the daily soil water balance were used in Equation (2) for vegetation types reliant solely on precipitation. Since the daily soil water balance accounts for variable precipitation, the ET_v from vegetation reliant on precipitation varies from year to year. As a reference, the long-term annual average K_v values for these vegetation types were calculated from daily soil water balances for each planning area and are summarized in Table 1.

The K_v values summarized in Table 1 for non-water stressed vegetation were used in Eq. (3) to estimate monthly average ET_v for vegetation types that had access to full year-round water supply by planning area. Long-term average ET_v values for all vegetation types are shown in Table 2 (Howes et al., 2015).

3.4.2 Vegetation Areas

The vegetation present on the Valley Floor under natural conditions included rainfed and perennial grasslands, vernal pools, permanent and seasonal wetlands, valley/foothill hardwood, riparian forest, saltbush, and chaparral (Howes et al., 2015; Barbour et al., 1993; Garone, 2011; Küchler, 1977). The areal extent of each type of vegetation was estimated from historic maps and contemporary estimates based on historic sources (Hall, 1887; Burcham, 1957; Küchler, 1977; Roberts et al., 1977; Dutzi, 1978; Fox, 1987; TBI, 1998; CSU Chico, 2003; Garone, 2011; Whipple et al., 2012; Fox and Sears, 2014), supplemented by early soil surveys for vernals pools (Holmes et al., 1915; Nelson et al., 1918; Strahorn et al., 1911; Lapham et al., 1909; Sweet et al., 1909; Holmes and Eckmann, 1912; Mann et al., 1911; Lapham and Holmes, 1908; Lapham et al., 1904; Watson et al., 1929).

Most of these vegetation maps focused on a single type of vegetation so we were unable to use them as our primary source. Further, we were unable to piece the more limited coverage maps together in any meaningful way as they used different vegetation classification systems and different study areas; even this collection of maps did not cover the entire Valley Floor study area. Thus, we based our natural vegetation estimates on the California State University at Chico ("CSU Chico") pre-1900 map, which covered most of the Valley Floor.

The CSU Chico study reviewed and digitized approximately 700 historic maps from numerous collections in public libraries. These sources were pulled together in a series of maps, including a "Pre-1900 Historic Vegetation Map." We used the pre-1900 Historic Vegetation Map as our

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base map, modified to cover the entire Valley Floor using Küchler (1977) and to further subdivide some of its vegetation classifications to match available evapotranspiration information.

CSU Chico characterized its pre-1900 map as "the best available historical vegetation information for the pre-1900 period" noting it provided "a snapshot of the most likely pre Euro-American vegetation cover" (CSU Chico, 2003). This map has been cited by others as representing natural vegetation (Bolger et al., 2011; Vaghti and Greco, 2007). It is based on a patchwork of sources, scales, and dates, with the earliest source map dating to 1874.

The accuracy of the CSU Chico pre-1900 map was confirmed to the extent feasible using GIS overlays with other available natural vegetation maps (Hall, 1887; Roberts et al., 1977; Dutzi, 1978; Fox, 1987; TBI, 1998; Garone, 2011; Whipple et al., 2012). Original shapefiles were used where available (Whipple et al., 2012; TBI, 1998; Küchler, 1977; CSU Chico, 2003). Other maps were scanned (400-dpi full color scanner), the scanned versions were georeferenced using various data layers (e.g., county, township), and the map features were digitized by hand using editing features in ArcMap. ArcMap's geoprocessing tools were used to determine vegetation areas (Fox and Sears, 2014).

~~We also compared T~~the natural vegetation areas estimated using these methods were~~as~~ also compared with those estimated by others. ~~We estimatedIn t~~This work ~~it was~~ estimated ~~that~~about 0.40 million hectares of permanent wetlands. Others have estimated 0.40 (Fox 1987) to 0.53 million hectares (Hilgard 1884, Shelton 1987) for slightly different Valley Floor boundaries. This work estimated about 1.62 million hectares of grasslands. Others have estimated 2.02 (TBI 1998) to 2.18 (Fox, 1987; Shelton 1987) million hectares for slightly different Valley Floor boundaries. ~~We~~The current study estimated~~showss of~~ approximately~~, about~~ 0.77 million hectares of vernal pool habitat in the Valley Floor outside of the floodplain. Others have estimated about 0.97 million hectares of vernal pool habitat (Holland 1978, 1998; Holland and Hollander 2007) for slightly different Valley Floor boundaries. This work also estimated 0.29 million hectares of riparian forest based on CSU Chico's map, which is low compared to estimates by others including 0.35, 0.38, 0.37, 0.58, and 0.65 million hectares estimated by Shelton (1987), Roberts et al. (1977) , Katibah (1984) , Fox (1987), and Warner and Hendrix (1985), respectively, for slightly different Valley Floor boundaries.

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However, as the CSU Chico maps and other sources were based on maps prepared after significant modifications to the landscape had already occurred, they may underestimate some types of natural vegetation (Thompson, 1957; Whipple et al., 2012; CSG, 1862). It follows that reliance on these maps may underestimate evapotranspiration and thereby overestimate natural Delta outflow. Riparian forests, for example, were cleared early to make way for cities and farms and harvested to supply fuel for steamboats traversing the rivers in support of the Gold Rush (Whipple et al., 2012). Widespread conversion of wetlands into agricultural uses began in the 1850s when they were leveed, drained, cleared, leveled or filled; water entering them was impounded, diverted, or drained; and sloughs and crevasses closed to dry out the land (Whipple et al., 2012; Frayer et al., 1989; CSG, 1862). The great wheat bonanza that transformed much of the Central Valley into farmland was well underway by 1874, the date of the earliest historic map in the collection considered by CSU Chico.

The results of our natural vegetation area analysis, based on available historic maps and soil surveys, are summarized in Figure 4 and Table 3. These areas represent the starting point for our natural flow estimate. We call this starting point "Case I".

Case I represents long-term annual average conditions. These areas are not representative of individual years due to climate-driven variations, which primarily affected grasslands and wetlands. Area size, especially of rainfed grasslands and vernal pools, likely varied from year to year with the amount of precipitation falling on the Valley Floor and surrounding mountains.

3.4.3 Sensitivity Analysis

A sensitivity analysis was performed to address the uncertain~~i~~ty in both natural vegetation areas and evapotranspiration rates. The areal extent of most types of vegetation was not measured or even observed by botanists in its natural state. Further, the water used by some classes of natural vegetation, such as vernal pools and valley oak savannas, has never been measured in the Valley Floor while the natural water supply is largely based on measurements of rim watershed stream flows or impairments thereof and precipitation. Thus, we formulated a series of cases, in which land use was varied, to explore the range in natural vegetation water use. The cases were selected to address key uncertainties associated with classifying vegetation areas. The eight cases we studied are summarized in Table 4.

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As grasslands (including vernal pools) and valley/foothill hardwood classifications represent the greatest portions of the Valley floor (see Table 3), our cases focus on these two vegetation classifications. The extent of permanent wetlands, the next largest vegetation classification in the Valley Floor, was extensively surveyed in the 1850s (CSG, 1856; CSG, 1862; Anonymous, 1861; Flushman, 2002; Thompson, 1957) and is considered to be accurately estimated in Case I (Table 3). Further, the evapotranspiration from these wetlands has been well studied (Howes et al., 2015). Thus, we have confidence in our estimates of water use by permanent wetlands.

Grasslands occupied about half of the Valley Floor area or about 16,000 km^2 out of 34,000 km^2 (Table 3). The composition of these grasslands (e.g., the fraction that was perennial, rainfed, and vernal pool) is unknown, as rapid and widespread modifications occurred before any botanical study (Heady et al., 1992; Holmes and Rice, 1996; Holstein, 2001; Burcham, 1957; Garone, 2011). Some have attempted to estimate vernal pool area (Holland, 1978; Holland, 1998; Holland and Hollander, 2007), but we are not aware of any attempts to estimate the area of perennial and rainfed grasslands.

There is significant controversy over the original composition of grasslands. Some argue pristine grasslands were perennial bunchgrasses (Heady, 1988; Küchler, 1977; Bartolome et al., 2007) while others argue they were dominated by annual forbs (Schiffman, 2007; Holstein, 2001). A discussion of this controversy is provided in Garone (2011). Finally, large expanses of lands classified as "grasslands" by others (Küchler, 1977; Fox, 1987; TBI, 1998; CSU Chico, 2003) were probably vernal pool seasonal wetlands supported by perched aquifers (Zedler, 2003; Holland and Hollander, 2007; Fox and Sears, 2014). Due to these unknowns and controversies, we used six cases to explore the effect of grassland composition on natural water use, the base case compared to five variants.

In Case I, all grassland areas outside of the floodplain were classified as either vernal pool (based on soil surveys) or rainfed grassland, as shown in Figure 4 and Table 3. We then varied the rainfed portion to assume it was vernal pool (Case II) and perennial grassland (Case III) to bound the likely range.

These three constant-area grassland cases resulted in many negative San Joaquin Basin annual outflows, mostly in dry and critical years. One explanation for this outcome is that the grasslands may have been predominately rainfed in the San Joaquin Basin since this basin is

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much drier than the other two. Another explanation is that our water balance model assumed the net change in groundwater storage was zero on a long-term basis, which may not be valid on a yearly and basin-wide basis.

Groundwater that was recharged in wet and above normal years could have supplied the water needs of natural vegetation in subsequent years. Failure to account for these potential inter-annual sources of water could bias individual year water balances and could result in negative basin outflows for individual years (particularly critical and dry years that follow very wet years). Negative basin annual outflows were primarily limited to the San Joaquin Basin.

Thus, in Case IV, all grasslands in the San Joaquin Basin were classified as rainfed grasslands in an attempt to address this possibility, while grasslands in the Sacramento and Delta Basins were classified as a mix of vernal pool and perennial as in Case III. A similar consideration led to the classification of seasonal wetlands in the San Joaquin Basin as rainfed grasslands (Case VIII, discussed later).

~~Case IV is similar to Case III, except that all San Joaquin Basin grasslands were classified as rainfed.~~ We also discounted the scenario of grasslands being rainfed valley-wide as unlikely, given that our work and the work of Holland and Hollander (2007) established that a significant fraction of the Valley Floor was vernal pool habitat. Some of these grassland areas, particularly within the flood basins, were likely seasonal wetlands or lakes and ponds (Whipple et al., 2012) with higher water uses, but we had no basis for estimating these areas.

It was generally assumed that vegetation areas are constant from year to year in cases I to IV, which is reasonable for a long-term annual average. However, this assumption is an over-simplification when applied to individual years because vegetation area likely varied in response to climate, especially the amount and timing of precipitation and resulting riverbank overflow. The floodplain boundary, for example, would have varied significantly depending on the amount and timing of runoff, which would have affected vegetation both inside and outside of the floodplain. In July 1853, for example, engineers surveying a route for a railroad in the San Joaquin Valley reported: "The river [San Joaquin] had overflowed its banks, and the valley was one vast sheet of water, from 25 to 30 miles broad, and approaching within four to five miles of the hills" (Williamson, 1853). The average floodplain boundary (CDPW, 1931a, 1931b) was typically over 20 miles from these hills. We used the average floodplain boundary to estimate

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some vegetation types, such as seasonal wetlands within "other floodplain habitat," which would yield inaccuracies when used for individual years.

Grasslands are the vegetation type most likely to respond significantly to climate. Thus, in Cases V and VI, the mix of rainfed and perennial grasslands was varied based on the volume of rim inflow to the Sacramento and San Joaquin basins. Vegetation areas in Case V are identical to Case I, except grassland areas not classified as vernal pools are assumed to be a mix of rainfed and perennial grasslands that vary from year to year based on the annual runoff volume as measured by the Eight River Index (CDWR 2013). Grassland areas are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and the driest year.

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Vegetation areas in Case VI are identical to Case I, except vernal pools are assumed to be a mix of rainfed and perennial grassland. Aggregate grasslands are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and the driest year.

We believe Cases V and VI most closely represent water use under natural conditions as it is likely that vegetation varied in this fashion. It is likely that seasonal wetlands varied in a similar fashion, extending further outside of the flood basins in wet years than in dry or critical (Whipple et al., 2012). However, we did not have sufficient data to evaluate this case.

We defined two additional vegetation area cases to explore the uncertainty of natural Delta outflow due to evapotranspiration and areal extent of valley foothill hardwoods (Case VII) and wetlands (Case VIII).

Case VII was included to explore the effect of valley/foothill hardwoods composition on natural Delta outflow. This case primarily affects Sacramento Basin outflow as 86% of the hardwood vegetation, or 5,300 km^2, are in this basin. This vegetation class was subdivided into foothill hardwood, present at higher elevations with deeper water tables, and valley oak savannas, present in the Valley Floor where water tables were shallow, for purposes of estimating evapotranspiration (Howes et al., 2015). Foothill hardwoods likely relied on soil moisture as the water table was generally deeper at these higher elevation areas than on the Valley Floor. Valley oak savannas, on the other hand, had deep root systems (Howes et al., 2015) that tapped the

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shallower groundwater at lower elevations (Bertoldi et al., 1991; Bryan, 1915; Kooser et al., 1861).

We had no basis for reliably subdividing valley/foothill hardwood land areas into subclasses. Küchler (1977) suggests about 65% was foothill hardwoods. Thus, we evaluated a range. In Case I, we assumed that 100% of valley/foothill hardwood was foothill hardwood. In Case VII, we assumed 100% was valley oak savanna, holding all other land areas constant as in Table 3.

Case VIII classifies San Joaquin Basin seasonal wetlands as rainfed grasslands. The San Joquin Basin was modeled differently based on our annual water balances, as discussed above, supplemented by sSoil surveys, eyewitness accounts, and the basin's relatively dry hydrology which suggest that rainfed grasslands (rather than seasonal wetland) is a plausible alternate vegetation classification for seasonal wetlands.

4 Results

The water balance methodology described previously was used to estimate annual average Delta outflow under natural conditions for each year of the 88-year hydrologic sequence (1922-2009). A long-term annual average was computed from individual yearly results and compared with CDWR's (2012, 2007) estimates of long-term annual average Delta outflow under current conditions and unimpaired conditions for a similar period of record.

The results of our natural Delta outflow water balances for eight land use cases are summarized in Table 5 and illustrated in Figure 5. Under natural conditions, native vegetation used 27.1 to 36.1 billion m^3/yr of the natural water supply, falling as precipitation in the mountain ranges surrounding the Valley Floor and on the Valley Floor itself. This amounts to 54% to 72% of the total supply of 50.1 billion m^3/yr–. The water that was not evapotranspired or evaporated, ranging from 14.0 to 23.0 billion m^3/yr , flowed into the Delta and San Francisco Bay. These results are consistent with those reported by others (Shelton, 1987; Bolger et al., 2011; Fox, 1987).

The resulting evapotranspiration-–to-–precipitation (ET/P) ratios, 0.54 to 0.72 are, estimated as total water useET from Table 5 divided by the sum of Valley Floor Pprecipitation (15.9 billion m^3/yr) and rim inflows (34.2 billion m^3/yr), and are consistent with ET/P ratios reported by others– (Sanford and Selnick, 2013). The Valley Floor vegetation described in this work was not

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sustained by precipitation falling on the Valley Floor. The Valley Floor also~~ itself, but rather~~ used large quantities of runoff from surrounding watersheds that was not consumed in those watersheds but was made available for consumptive use through the seasonal flooding cycle. Therefore, rim inflows effectively act as precipitation to the Valley Floor.~~.~~

In sum, w~~W~~e believe that Cases V and VI, in which the mix of rainfed and perennial grasslands was varied based on the volume of rim inflow to the Sacramento and San Joaquin basins, most closely represent water ~~use~~ consumed under natural conditions. In these cases, native vegetation ~~used~~ consumed 30.4 to 29.7 billion m^3/yr or about 60% of the natural supply. About 41% of the native vegetation water use in these two cases was consumed by the grassland-vernal pool complex occupying the area between the foothills and the floodplain. About 34% of the native vegetation water use was consumed by permanent and seasonal wetlands, largely within the floodplain. The balance of the native vegetation water use was consumed by riparian vegetation (13%), foothill hardwoods (9%), and saltbush, chaparral, and open water surfaces (3%).

In comparison, the current-level, long-term annual average Delta outflow is 19.5 billion m^3/yr (CDWR, 2012). This estimate was developed using a reservoir system operations model (Draper et al., 2004) and assumes a 2011 level of development for an 82-year hydrologic sequence (1922 to 2003). The current long-term annual average water supply of 51.6 billion m^3/yr estimated by CDWR (2012) exceeds the natural water supply in our analysis by 1.5 billion m^3/yr due to (1) groundwater overdraft of 0.9 billion m^3/yr in the Sacramento and San Joaquin Basins and (2) Sacramento River Basin imports of 0.6 billion m^3/yr from the U.S. Bureau of Reclamation Trinity River Diversion Project, a project that transfers water from Lewiston Reservoir through the Clear Creek Tunnel to the Sacramento River (CDWR, 2012). ~~Thus, 62% of the current water supply or 31.9 billion m^3/yr is consumed by irrigation, municipal, industrial, and other uses under current conditions, based on the 2011 level of development.~~

The long-term annual average current level Delta outflow of 19.5 billion m^3/yr falls within the range of estimated natural outflows as shown in ~~Table 5~~Figure 6 for the same period of record (14.0 to 23.0 billion m^3/yr). The current level water balance indicates that 62% of the water supply is currently consumed by irrigation, municipal, industrial, and other uses, based on the 2011 level of development (CDWR, 2013b). This estimate is roughly the midpoint of the range of estimated natural water use (54% to 72%) and indistinguishable from our best estimates of natural outflow in cases V and VI (60%).

Thus, current and natural Delta outflows, when reported for the same climatic conditions, are very similar because natural vegetation used nearly as much water (27.1 to 36.1 billion m^3/yr) as is consumed currently (31.9 b~~26.0 b~~illion m^3/yr) for agriculture, municipal, industrial, and other uses. Further, the current and natural Delta outflow estimates are statistically indistinguishable due to uncertainties described elsewhere.

In sum, reconfiguring the natural water supply to accommodate new land uses (e.g., see~~compare~~ Figure 4~~ with Figure 5~~), mitigate flooding, and redistribute the water supply in time and space has not changed the annual average amount of freshwater reaching San Francisco Bay from the Central Valley, when controlled for climate. This is the case because natural vegetation ~~(Figure 4)~~ consumed about as much water as is currently used by the new land uses within the Valley Floor~~ (Figure 5)~~ as well as outside of it.

We believe our natural Delta outflow estimates were based on conservative assumptions that will tend to underestimate evapotranspiration and thus overestimate natural Delta outflows. Noteworthy conservative assumptions include: (1) all of the permanent wetlands is assumed to be "large stand", thereby ignoring higher water-using "small stand" wetlands and (2) the maps and soil surveys used to estimate natural vegetation ~~areas~~ underestimate the extent of some types of natural vegetation, such as wetlands and vernal pools, because~~ as~~ significant modifications had been made to the landscape prior to the date of its earliest source (1874).

5 Discussion

This study shows that long-term annual average current and natural outflows fall within the same range, when controlled for climatic conditions. This occurs as the amount of water currently used from Valley Floor watersheds for agriculture, domestic, industrial, and other uses is about equal to the amount of water that would be used if the existing engineered system were replaced by natural vegetation.

An estimate of natural Delta outflows is important as reduction in the volume of freshwater reaching the San Francisco Bay-Delta Estuary due to the current level of development has frequently been advanced as one of the causes for the decline in abundance of native species.

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Further, estimates of hypothetical natural outflow (so-called "unimpaired" outflows) have been proposed to regulate current Delta outflows in an effort to restore ecological health of the estuary. ~~However, prior to our work, no one had attempted to estimate natural outflows.~~ This work indicates that restoring flows to annual average natural outflows are unlikely to restore ecosystem health because they are indistinguishable from annual average current outflows.

The reduced outflow hypothesis advanced by some as a cause of declines in native fish abundance is typically based on "unimpaired" flows of 34.3 billion m^3/yr published by CDWR (2007). These "unimpaired" flows are hypothetical flows that never existed. ~~They assume the same water supply (50.1 billion m^3/yr) as our natural water balance, but current landscape conditions. Thus, unimpaired flows are not natural flows.~~ CDWR (2007) differentiates "unimpaired" Delta outflow from "natural" Delta outflow by characterizing them as:

runoff that would have occurred had water flow remained unaltered in rivers and streams instead of stored in reservoir, imported, exported, or diverted. The data is a measure of the total water supply available for all uses after removing the impacts of most upstream alterations as they occurred over the years. Alterations such as channel improvements, levees, and flood bypasses are assumed to exist.

The long-term annual average unimpaired Delta outflow estimate of 34.3 billion m^3/yr assumes the same rim inflows and Valley Floor precipitation used in our natural water balances in Table 5. However, rather than reducing water supply to account for water use associated with the full extent of natural vegetation in the Valley Floor, the unimpaired outflow calculation assumes that water use upstream of the Delta is limited to only Valley Floor precipitation (CDWR, 2007). In other words, the unimpaired outflow calculation assumes the only vegetation present outside of the Delta was perennial grasslands with no access to groundwater. It ignores the presence of perennial grasslands, vernal pools, wetlands, riparian forest, and valley oak savannahs.

Thus, the unimpaired outflow calculation effectively assumes rim inflows pass through the Valley Floor and arrive in the Delta in the current system of channel improvements, levees and flood bypasses (i.e., the difference between the natural water supply of 50.1 billion m^3/yr and Valley Floor precipitation of 15.9 billion m^3/yr is 34.2 billion m^3/yr). Thus, by definition, unimpaired Delta outflow calculations provide a high estimate when used as a surrogate for natural Delta outflow.

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In spite of CDWR's caveats of its theoretical calculation of "unimpaired" Delta outflow from natural Delta outflow, unimpaired outflows have frequently been used as a surrogate measure of natural conditions, presumably because <u>no</u>~~an~~ estimate of natural Delta outflow was <u>published</u>~~unavailable~~ prior to this work. For example, Dynesius and Nilsson (1994) argue that the Bay-Delta watershed is "strongly affected" by fragmentation due to the difference between current Delta outflow and the Delta's reported "virgin mean annual discharge" of 34.8 billion m^3/yr, a quantity roughly equivalent to CDWR's long-term annual average unimpaired Delta outflow calculation published by CDWR at the time of this work. More recently, the California State Water Resources Control Board (CSWRCB, 2010) submitted a report to the state legislature suggesting a flow criterion of 75 percent of unimpaired Delta outflow from January through June "in order to preserve the attributes of the natural variable system to which native fish species are adapted". This suggested criterion was based on fishery protection alone and did not consider other beneficial uses of water in the estuary.

Native aquatic species evolved under natural landscape conditions. ~~A comparison of~~ Figure~~s~~ 4 ~~and 5~~ demonstrates that very little of the natural landscape remains. Thus, habitat restoration should be an important ingredient in restoring these species. <u>Understanding</u>~~An estimate of~~ natural Delta outflow<u> and how it interacts with the natural landscape</u> <u>will be</u>~~is~~ important to guide future restoration planning activities.

The Comprehensive Everglades Restoration Plan (CERP), for example, used natural system modeling to gain a better understanding of south Florida's hydrology prior to drainage and development. CERP, which was designed to restore the Everglades ecosystem while maintaining adequate flood protection and water supply for south Florida, is using insights gained by this modeling effort, in combination with other adaptive management tools, to formulate restoration plans and set targets (SFWMD, 2014).

California's Bay Delta Conservation Plan, another such planning activity, envisions a reversal of the Delta's ecosystem decline through protection and creation of approximately 590 km^2 of aquatic and terrestrial habitat (CDWR & USBR, 2013). By reconnecting floodplains, developing new marshes, and returning riverbanks to a more natural state, the plan is designed to boost food supplies and provide greater protection for native fisheries.

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6 Conclusions and Recommendations

This study found that the amount of water from the Valley Floor watershed currently consumed for agriculture, domestic, industrial, and other uses is roughly equal to the amount of water formerly used by native vegetation in this same watershed. Thus, Delta outflow, or the amount of freshwater reaching San Francisco Bay, is about the same under current conditions as under natural conditions, when controlled for climate.

This finding, which used a conventional water balance methodology and assumed contemporary climatic conditions for both natural and current landscapes, suggests that human disturbances to the landscape and hydrologic cycle have not significantly reduced the annual average volume of freshwater flows entering San Francisco Bay through the Delta. Rather, development has simply redistributed flows from natural vegetation to other beneficial uses. Thus, it is unlikely that observed declines in native freshwater aquatic species are ~~unlikely~~ due to reduction in~~ theis a result of~~ annual average Delta outflow. ~~Thus, it is unlikely that reduced annual average freshwater flows have contributed to ecosystem decline in the estuary~~.

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Another key finding of this study is that "unimpaired" Delta outflow calculations significantly overestimate natural Delta outflow as they fail to include consumptive use by natural vegetation in the Valley Floor other than rainfed grasslands. Therefore, unimpaired Delta outflow calculations should not be used as a surrogate measure of natural conditions or to set flow standards to restore ecosystem health.

Several limitations associated with this work point to areas for future research. The simple water balance methodology utilized in this paper is an appropriate reconnaissance-level step in reconstructing the natural hydrology of a complex system. However, this simple approach is unable to explore several important and relevant questions.

First, our analysis only considers long-term annual averages and does not evaluate inter- and intra-annual variability of natural Delta outflow. Ecosystems respond to flows at time scales much shorter than annual. Thus, future work should consider these shorter time scales.

Second, our analysis does not account for complex interactions between groundwater and surface water. These interactions would place important limits on water availability to vegetation in a natural landscape on a shorter time scale.

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Third, many vegetation land areas likely varied with the wetness of the year. We attempted to address this using a sensitivity analysis in which grassland/vernal pools areas were varied as a function of rim inflows and other assumptions.

Finally, we assumed natural evapotranspiration rates for vegetation types with a continuous water supply, e.g., permanent wetlands, are constant over the period of record. They likely varied as a function of climate. Future work should include a sensitivity analysis of vegetation coefficient ranges such as those shown in Howes et al. (2015).

We recommend future research in several areas of historical landscape ecology, hydrology and estuarine hydrodynamics to address these limitations to support on-going regulatory and habitat restoration activities in the San Francisco Bay-Delta watershed, including:

- refined natural vegetation mapping in the Sacramento and San Joaquin Basins, following work in the Delta reported by Whipple et al. (2012);
- evapotranspiration from vernal pools and seasonal wetlands;
- interactions between groundwater and surface water under natural conditions;
- inter- and intra-annual variability of natural Delta outflows;
- natural watershed geomorphology; and
- natural estuarine salinity transport

We recommend that integrated groundwater-surface water models, digital elevation models and hydrodynamic models be developed to support this research. Several collaborative efforts are currently underway to develop such models (Draper, 2014; Kadir and Huang, 2014; Grossinger et al., 2014; Fleenor et al., 2014; DeGeorge and Andrews, 2014). Finally, we recommend future research be conducted to compare the evolution of the San Francisco Bay-Delta watershed with other watersheds around the world.

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Table 1. Monthly vegetation coefficients (K_v) for non-water stressed and rainfed vegetation (Howes et al., 2015)

	Month											
Vegetation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rainfed Grassland[1]	0.78	0.72	0.64	0.58	0.35	0.06	0.00	0.00	0.03	0.16	0.47	0.73
Perennial Grassland	0.55	0.55	0.60	0.95	1.00	1.05	1.10	1.15	1.10	1.00	0.85	0.85
Vernal Pool	0.65	0.70	0.80	1.00	1.05	0.85	0.50	0.15	0.10	0.10	0.25	0.60
Large Stand Wetland	0.70	0.70	0.80	1.00	1.05	1.20	1.20	1.20	1.05	1.10	1.00	0.75
Small Stand Wetland	1.00	1.10	1.50	1.50	1.60	1.70	1.90	1.60	1.50	1.20	1.15	1.00
Foothill Hardwood[1]	0.80	0.77	0.69	0.61	0.52	0.20	0.01	0.01	0.03	0.15	0.46	0.71
Valley Oak Savanna[1]	0.80	0.77	0.69	0.62	0.54	0.40	0.40	0.40	0.40	0.41	0.55	0.71
Seasonal Wetland	0.70	0.70	0.80	1.00	1.05	1.10	1.10	1.15	0.75	0.80	0.80	0.75
Riparian Forest	0.80	0.80	0.80	0.80	0.90	1.00	1.10	1.20	1.20	1.15	1.00	0.85
Saltbush	0.30	0.30	0.30	0.35	0.45	0.50	0.60	0.55	0.45	0.35	0.40	0.35
Chaparral[1]	0.55	0.61	0.54	0.40	0.22	0.03	0.01	0.01	0.03	0.14	0.40	0.57
Aquatic Surface	0.65	0.70	0.75	0.80	1.05	1.05	1.05	1.05	1.05	1.00	0.80	0.60

[1]*Evapotranspiration from rainfed vegetation was estimated from a daily soil water balance. Valley oak savanna K_v during the summer and fall was estimated to be 0.4 to account for groundwater contribution. The vegetation coefficients shown are averages over the 88-year period and all Valley Floor planning areas.*

MARKUP VERSION

Table 2. Annual average evapotranspiration rates ET_v (cm/yr)

Basin	Planning Area	Rainfed Grassland	Perennial Grassland	Vernal Pool	Large Stand Wetland	Small Stand Wetland	Seasonal Wetland	Foothill Hardwood	Valley Oak Savanna	Riparian Forest	Saltbush	Chaparral	Aquatic Surface
Sacramento	502	39.1	130.1	75.3	139.5	204.3	131.1	45.1	67.1	134.1	60.2	29.5	127.4
	503	39.1	130.1	75.3	139.5	204.3	131.1	45.1	67.1	134.1	60.2	29.5	127.4
	504	34.0	128.9	73.9	137.8	201.7	129.4	40.2	64.0	132.5	59.6	28.8	125.8
	505	32.8	135.9	77.9	145.1	212.5	136.2	40.2	67.1	139.6	62.7	24.7	132.5
	506	32.4	135.0	77.7	144.2	211.3	135.5	39.8	67.1	138.7	62.3	25.0	131.7
	507	35.2	139.2	80.1	148.7	217.9	139.7	42.7	70.1	143.0	64.3	26.9	135.8
	508	36.6	143.3	82.3	152.4	222.5	140.2	42.7	73.2	146.3	67.1	27.4	140.2
	509	32.8	135.9	77.9	145.1	212.5	136.2	40.2	67.1	139.6	62.7	24.7	132.5
Delta	510	31.2	136.8	78.5	146.0	213.8	137.0	38.6	67.1	140.4	63.1	23.2	133.3
	602	27.2	121.3	70.3	129.5	189.8	121.8	33.3	57.9	124.6	55.9	19.3	118.3
San Joaquin	511	34.8	143.3	81.8	153.0	224.1	143.5	42.6	73.2	147.1	66.2	26.4	139.7
	601	27.4	113.5	65.5	121.1	177.4	113.9	32.3	54.9	116.6	52.3	19.0	110.6
	603	33.7	142.7	81.9	152.3	223.3	143.0	41.5	70.1	146.4	65.9	25.5	139.1
	604	30.5	137.2	79.2	149.4	213.4	134.1	39.6	67.1	140.2	64.0	24.4	134.1
	605	24.4	134.1	79.2	146.3	213.4	134.1	30.5	61.0	140.2	64.0	18.3	131.1
	606	24.0	135.6	78.4	144.7	212.1	136.1	31.2	61.0	139.2	62.6	17.4	132.2
	607	29.3	140.2	80.9	149.6	219.5	140.6	36.8	67.1	143.8	64.7	21.6	136.7
	608	28.9	144.6	83.8	154.3	226.4	145.0	36.6	70.1	148.2	66.7	21.5	141.0
	609	29.0	152.1	87.5	162.2	238.0	152.2	37.2	70.1	155.8	70.2	22.0	148.2
	610	29.0	152.1	87.5	162.2	238.0	152.2	37.2	70.1	155.8	70.2	22.0	148.2

MARKUP VERSION

Table 3. Area of natural vegetation (A_v) by planning area within the Valley Floor, Case I (Hectares)

Valley	Planning Area	Rainfed Grasslands	Vernal Pool	Permanent Wetland	Seasonal Wetland	Valley/ Foothill Hardwood	Riparian Forest	Saltbush	Chaparral	Aquatic Surface	Total
Sacramento	502	0	0	0	0	692	0	0	0	0	692
	503	114,308	25,046	7	2	130,205	33,271	0	7,478	1,253	311,570
	504	52,570	433	96	977	78,027	34,720	0	39	807	167,667
	505	0	0	0	0	31	0	0	2,170	0	2,201
	506	140,301	94,683	50,395	19,679	71,054	43,383	0	9,541	2,429	431,466
	507	19,523	33,515	60,751	102,700	75,491	80,467	0	0	3,274	375,721
	508	7,289	3,712	0	0	86,369	5,407	0	0	590	103,368
	509	65,863	42,392	27,454	5,395	58,148	25,913	0	22,000	610	247,775
	511	18,066	74,895	20,989	25,425	51,101	17,408	0	0	3,116	211,000
Delta	510	718	4,263	91,810	10,550	21	760	0	0	5,240	113,361
	602	25,265	8,533	115,385	9,128	34	594	0	0	2,858	161,798
San Joaquin	601	3,885	3,874	0	2	0	1	0	0	274	8,037
	603	47,777	59,435	5,117	55,734	80,998	16,614	0	157	629	266,461
	604	1,098	0	0	0	741	311	0	0	0	2,149
	605	4,924	406	0	0	0	0	0	0	0	5,331
	606	83,099	70,915	12,084	57,570	0	1,281	41,405	32	1,136	267,523
	607	69,411	64,097	3,295	9,099	1,355	10,574	0	0	820	158,651
	608	66,786	51,142	3,037	4,945	1,689	12,797	0	0	478	140,873
	609	123,728	242,041	17,323	18,450	501	8,462	8,099	0	1,258	419,863
	610	6,547	376	0	0	67	4	0	0	0	6,995
TOTAL		**851,158**	**779,758**	**407,744**	**319,657**	**636,525**	**291,966**	**49,505**	**41,416**	**24,771**	**3,402,501**

Note: Case I assumes: (1) no perennial grasslands; (2) all permanent wetlands are large stand; and (3) all valley/foothill hardwoods are foothill hardwoods.

MARKUP VERSION

Table 4. Water Balance Cases

Case		Grassland Assumptions		Hardwood Assumptions
		Sacramento & Delta Basins	San Joaquin Basin	
Grasslands – Constant Area	I	Mix of rainfed grassland and vernal pools	Mix of rainfed grassland and vernal pools	Foothill
	II	Vernal pools	Vernal pools	Foothill
	III	Mix of perennial grassland and vernal pools	Mix of perennial grassland and vernal pools	Foothill
	IV	Mix of perennial grassland and vernal pools	Rainfed grassland	Foothill
Grasslands – Variable Area	V	Mix of rainfed and perennial grassland and vernal pools (1)	Mix of rainfed and perennial grassland and vernal pools (1)	Foothill
	VI	Mix of rainfed and perennial grassland (2)	Mix of rainfed and perennial grassland (2)	Foothill
Other	VII	Mix of rainfed grassland and vernal pools	Mix of rainfed grassland and vernal pools	Valley Oak Savanna
	VIII	Mix of perennial grassland and vernal pools	Rainfed grassland (3)	Foothill

(1) Vegetation areas are identical to Case I, except grassland areas not classified as vernal pools are assumed to be a mix of rainfed and perennial grassland that varies from year to year based on the annual runoff volume as measured by the Eight River Index (CDWR 2013a). Grassland areas are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and driest year.

(2) Vegetation areas are identical to Case I, except vernal pools are assumed to be a mix of rainfed and perennial grassland. Aggregate grasslands are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and driest year.

(3) Vegetation areas are identical to Case IV, except seasonal wetlands within the floodplain are assumed to be rainfed grasslands.

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Table 5. Natural water balance 1922-2009 Valley Floor (billion m^3/yr)

Water Supply		Water Use (billion m^3/yr)							
Inflow	34.2		Grasslands – Constant Area			Grasslands – Variable Area		Other Vegetation	
Precipitation	15.9								
Total Water Supply	**50.1**	**Case I**	**Case II**	**Case III**	**Case IV**	**Case V**	**Case VI**	**Case VII**	**Case VIII**
Sacramento Basin									
Rainfed Grasslands		1.5	0.0	0.0	0.0	0.9	1.5	1.5	0.0
Perennial Grasslands		0.0	0.0	5.6	5.6	2.1	3.6	0.0	5.6
Vernal Pool		2.2	5.4	2.2	2.2	2.2	0.0	2.2	2.2
Large Stand Wetland		2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Seasonal Wetland		2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Foothill Hardwood		2.3	2.3	2.3	2.3	2.3	2.3	0.0	2.3
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0
Riparian Forest		3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Saltbush		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chaparral		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		14.2	**15.9**	**18.2**	**18.2**	**15.7**	**15.5**	**15.5**	**18.2**
Delta									
Rainfed Grassland		0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
Perennial Grassland		0.0	0.0	0.4	0.4	0.1	0.1	0.0	0.4
Vernal Pool		0.1	0.3	0.1	0.1	0.1	0.0	0.1	0.1
Large Stand Wetland		2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Seasonal Wetland		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Foothill Hardwood		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Riparian Forest		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saltbush		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chaparral		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		3.5	**3.5**	**3.7**	**3.7**	**3.5**	**3.5**	**3.5**	**3.7**
San Joaquin Basin									
Rainfed Grasslands		1.1	0.0	0.0	2.6	0.7	1.5	1.1	3.0
Perennial Grasslands		0.0	0.0	5.8	0.0	2.2	5.1	0.0	0.0
Vernal Pools		4.2	7.5	4.2	0.0	4.2	0.0	4.2	0.0
Large Stand Wetlands		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Seasonal Wetland		2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0
Foothill Hardwoods		0.4	0.4	0.4	0.4	0.4	0.4	0.0	0.4
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0
Riparian Forest		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Saltbush		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Chaparral		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		9.5	**11.7**	**14.2**	**6.8**	**11.3**	**10.7**	**9.7**	**5.2**
Total Water Use		**27.1**	**31.1**	**36.1**	**28.7**	**30.4**	**29.7**	**28.7**	**27.1**
Delta Outflow = Total Water Supply – Total Water Use		**23.0**	**19.0**	**14.0**	**21.4**	**19.6**	**20.4**	**21.4**	**23.0**

MARKUP VERSION

Figure 1. California, current land classifications, and major tributaries feeding into and through the Central Valley.

Figure 2. Valley Floor Study Area showing the area that water use calculations were conducted by planning area and summarized by hydrologic basin. Planning Areas 502, 505, 508, 601, 604, 605 and 610 within the Valley Floor are too small to show on this map. Planning area boundaries were defined by CDWR (2005a, 2005b).

Figure 3. IdealizedIllustrated cross section of the valley floor under natural conditions.

Figure 4. Natural vegetation in the Valley Floor map portraying the areal extent of natural vegetation based on the "Case I" definition of grassland composition (i.e., all grassland area outside of the floodplain was classified as either vernal pool or rainfed grassland). Although this map represents a composite of several maps, the primary source of information comes from CSU Chico's pre-1900 Historic Vegetation Map (CSU Chico 2003) (left). Current land use on the Valley Floor (right).

Figure 5. Current land use on the Valley Floor.

Figure 56. Schematic showing the average (1922-2009) natural water balance results (billion m^3/yr).

Figure 6. Comparison of long-term (1922-2009) average annual Delta Outflow estimated based on unimpaired, current (2011) level, and the natural scenarios (Cases I-VII) examined in this study.