

Quantification of Record-Breaking Subsidence in California's San Joaquin Valley

Corresponding Author: Dr Matthew Lees

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Dr Lees,

Please allow us to sincerely apologise for the long delay in sending a decision on your manuscript titled "How to Manage Record-Breaking Subsidence in California's San Joaquin Valley?". It has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

We apologize for the delayed review process, and hope the comments would be help.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Teng Wang, PhD
Editorial Board Member
Communications Earth & Environment
0000-0003-3729-0139

Joe Aslin
Deputy Editor

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors implemented statistical approaches variogram and kriging to spatially interpolate missing subsidence records over San Joaquin Valley, California over 2011-2015 using GNSS measurements, thus fulfilling the data record of major subsidence periods in the Valley from 2007-2022. Previously, Ojha et al. 2019 employed an interpolation approach to interpolate GPS vertical components, though they did not generate any spatially continuous subsidence dataset for the period of interest. Implementing geospatial interpolation, included with elliptical correlation structure-based correction using

2007-2010 and 2015-2022 datasets, the authors take this study to the next step by generating spatially continuous subsidence raster for 2011-2015. In addition, the authors have estimated subsidence volumes over different subsiding timelines, which seem well within the range reported by various literature. The dataset along with the volumetric estimates of subsidence will be helpful to understand the true extent of subsidence in the missing period, analyze drivers that led to compaction of aquifer, and partake management decisions on how much head recovery is needed to stop compaction. The authors have discussed the consequences of current groundwater recharge practices, how they might not be sufficient to stop subsidence, and potential steps to stop consolidation. Overall, the manuscript is well written, and the authors have provided details to reproduce the results/analysis.

Minor comments:

- Reword the word 'relationship' as it is essentially not a relationship (if needed re-write the line) as the plot of drought periods and InSAR data processed are separate. (line 62)
- The authors should mention the lag-time effect of subsidence when mentioning the impacts of the generated datasets (around line 103-104 or in that paragraph). The complete record can help to lead effort to analyze lagged subsidence carried over from 2007-2010 period to some extent.
- In figure 6, use the same shading for representing drought periods as figure 1.
- In line 298, move '.' after ')' at the end of the paragraph.
- In line 322, remove '.' or rewrite the line.
- In Methods 1, mention that it has been applied for the 2007-2010 period.
- In Methods 3, it's mentioned that less than three points were assigned Nan value during interpolation. Also, it's mentioned that to remove directional bias, if there is more than 1 point only the nearest point was considered. This creates a conflict in the overall statement. Need further clarification/rewriting in the paragraph.

Md Fahim Hasan
Ph.D. Candidate
Colorado State University

Reviewer #2 (Remarks to the Author):

This article utilizes satellite geodetic techniques to measure land subsidence volume in the entire San Joaquin Valley. It effectively tracks the Valley-wide subsidence over the full post-2007 period and suggests that efforts to reduce excessive groundwater extraction should focus on the deep aquifers contributing to land subsidence and the areas most severely affected by land subsidence.

However, there are still some issues that need improvement:

1. The logical structure of the introduction is unclear and recommended to improve it.
2. It is noted from Figure 1 that GNSS stations are sparse in severely subsiding areas, and the discussion section also points out that the interpolation of GNSS is the main source of error. How can the authors ensure that the interpolation results meet accuracy requirements? Can experimental internal validation results be provided?
3. The article devotes a large portion to demonstrating how to calculate subsidence volumes from 2011 to 2015, with Figure 6 only showing the median estimate obtained during this period. Could detailed zoomed-in figures be provided?
4. The supplementation of land subsidence data from 2011 to 2015 enables the continuity of land subsidence data in the region after 2007. However, regarding the theme of the article on managing record-breaking subsidence in California's San Joaquin Valley, could it be inferred based on existing subsidence data from 2007 to 2010 and 2015 to 2022 that subsidence is concentrated in the main areas of El Nido and Corcoran? Could related management recommendations also be proposed? Is it necessary to calculate subsidence data for the period 2011 to 2015?
5. The statement from lines 273 to 276 suggesting that subsidence details are not important to explain negligible interpolation errors might be too weak. How can the overall subsidence value be deemed reliable?
6. What is the basis for setting the parameters of the variogram in Method 4?
7. What are the criteria for determining the effectiveness of the parameter fitting for the ellipse model in Method 4? Was cross-validation performed?
8. What is the universal accuracy and applicability of the algorithm to fill in missing subsidence data? It can be further elaborated, because the vertical deformation accuracy of GNSS may be lower than that of InSAR data.
9. The method of filling data gap has great significance in terms of data integrity, but what role can it play in understanding and preventing ground subsidence?

Reviewer #3 (Remarks to the Author):

The calculations and compilation of the complete record of total subsidence in the San Joaquin Valley is a needed and worthwhile scientific effort. The method for compiling the missing recent years is novel.

The statistical analyses and calculations of volumes appear valid and the work appears to be reproducible.

Conversely, the hydrologic inferences that support that the management angle should be thought through and substantiated or better documented.

I think the authors should reconsider the title starting on "How to manage" as it does not feel to be the strong focus of the article.

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Version 1:

Decision Letter:

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Dear Dr Lees,

Your manuscript titled "Quantification of Record-Breaking Subsidence in California's San Joaquin Valley Leads to Management Insights" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Teng Wang, PhD
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Joe Aslin
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REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

My concerns have been well addressed by the authors. I would like to suggest accepting for publication.

Reviewer #3 (Remarks to the Author):

This paper develops a method to quantify recent subsidence volumes in the San Joaquin Valley post 2006. To date, only numerical Hydrological models, spot measurements, and incomplete satellite measurements have been available. This quantification of subsidence post 2006 is useful for regional insights into groundwater and subsidence management. These subsidence volume rates could be used to help validate rates from numerical groundwater flow models. I think it is important to point out that although the rate has gone up, the locations of subsidence have changed (at least in some places and particularly the old maximum location).

The paper should influence managers to think more strategically in terms of subsidence management. In terms of management, the article effectively articulates that the subsidence historically and recently has been in the deeper parts of the system. The management technique suggested to move more pumping to the shallower system should be an effective approach in hydrogeologically acceptable locations, but managers should proceed cautiously and monitor this part of the system. There is limited evidence that some subsidence is beginning to occur in shallower parts of the system as the pumping is moved to shallower parts of the system.

Notes (not needed to be included in review):

Check caption figure 1, first reference to InSAR coverage is 2006-2010 and rest are 2007-2010. Please check.

Lines 379-383 include a reference to a model for overdraft rates (Brust et al., 2013). Seems like for completion it would be good to include Faunt et al. (2024) which has a similar, though slightly higher rate.

Lines 414-216 Are an oversimplification that does not take into consideration that during these periods the vast majority of pumping where finer grained materials were present was in these deeper parts of the aquifer. IF pumping moves to the shallower parts of the system that are semi-confined to confined, then these shallow parts of the aquifer are also likely to have subsidence. You don't want to get rid of one problem and create another. This should at least be mentioned here. I know later it is alluded to.

Lines 423-425 The geology is also much finer grained possibly making this injection less effective and also deeper than the Sacramento area.

Lines 435-438 A reference as to information on growers' credits would be useful.

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Response to Reviewers

We have considered all comments from the three reviewers. Here, we describe – for each comment - the changes we have made to the manuscript and/or explain why we did not make changes. We have numbered the comments.

Note: line numbers refer to the 'track changes' updated manuscript version, with all changes selected, unless mentioned otherwise.

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Reviewer 1

1.1 Reword the word 'relationship' as it is essentially not a relationship (if needed re-write the line) as the plot of drought periods and InSAR data processed are separate. (line 62)

We have clarified the wording as suggested.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~) (lines 122-124): Figure 1a shows the **relative timings of** ~~relationship between~~ the main periods for which InSAR data have been processed in the San Joaquin Valley and periods of drought.

1.2 The authors should mention the lag-time effect of subsidence when mentioning the impacts of the generated datasets (around line 103-104 or in that paragraph). The complete record can help to lead effort to analyze lagged subsidence carried over from 2007-2010 period to some extent.

Changes not made. Explanation:

The time-lag between head levels and subsidence is important for subsidence science and management, and we agree that our results could be used to analyze this aspect of subsidence. However, since we do not specifically address that in this paper, we opt not to insert a reference to the time-lag effect.

1.3 In figure 6, use the same shading for representing drought periods as figure 1.

We have updated Figure 6 to use the same drought colors as in Figure 1. Since each of the 2007-2010, 2012-2016 and 2020-2022 droughts contained sub-periods of different drought intensities, we used the color corresponding to the drought intensity that was seen in the largest portion of each period.

1.4 In line 298, move '.' after ')' at the end of the paragraph.

Rephrased to tidy the punctuation in this sentence.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~) (lines 1207-1209): (The expansion of water represents a third physical process, but – **as shown by Williamson et al., (1989)** – this is a negligible source of water in the San Joaquin Valley. (~~Williamson et al. (1989).~~)

1.5 In line 322, remove ':' or rewrite the line.

Change not made. Explanation:

On stylistic grounds, we prefer the version with the ':'.

1.6 In Methods 1, mention that it has been applied for the 2007-2010 period.

We make the following changes to clarify the specific period that the method was applied over. (Note that, due to another reviewer's comment, we now consider three periods and have made all of those clear in Methods 1.)

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1548-1549): First, we digitized the displacement contours of **June 2007-December 2010 subsidence** from Figure 1 of Farr et al. (2015).
(lines 1565-1566): **We downloaded the pixel-level December 2006 – January 2010 subsidence data from the repository at Ojha et al. (2022).**
(lines 1578-1579): **First, we digitized the displacement contours of January 2008 – January 2010 subsidence from Figure 17 of Sneed et al. (2018).**

1.7 In Methods 3, it's mentioned that less than three points were assigned Nan value during interpolation. Also, it's mentioned that to remove directional bias, if there is more than 1 point only the nearest point was considered. This creates a conflict in the overall statement. Need further clarification/rewriting in the paragraph.

We have made changes to clarify the averaging procedure.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1641-1645): To reduce directional bias, in the situation where there ~~was more than one value within 60 km in the same direction (defined as within 1 azimuthal degree),~~ **were a) more than three measurements within 60 km and b) two or more of those measurements fell in the same sector, where we defined 360 sectors each of 1 azimuthal angular width around the pixel of interest,** only the nearest value **in each sector** was used in the interpolation.

Reviewer 2

2.1 The logical structure of the introduction is unclear and recommended to improve it.

We reviewed the introduction and we made two substantial changes to increase clarity:

1. We reincorporated the paragraph on global/wider impact to a new section at the end called "Historic context"

Original paragraph, with parts that were kept in **BOLD**, parts that were kept with modification in ***BOLD ITALICS***, and parts that were deleted in ~~strikethrough~~.

~~"Quantifying the San Joaquin Valley subsidence during the post-2007 period can have an impact at the global scale by motivating a commitment in California to allocate the resources required to address the issue. In recent years, several high-profile studies have highlighted the many urban areas globally facing a flooding threat as a consequence of subsidence resulting from groundwater extraction (Hasan et al., 2023; Herrera-García et al., 2021; Nicholls et al., 2021), yet few of these threatened areas have access to the same financial and institutional resources as California. In the historic period, the San Joaquin Valley subsidence was met by a concerted scientific effort that led to the development of the aquitard drainage model and the extensometer, key advances that have continued global importance to this day (Gambolati & Teatini, 2021; Holzer, 1998). The dramatic scale of the subsidence provided a major impetus for the scientific research that allowed these advances to be made. Here, we hope that quantifying the Valley-scale subsidence can catalyze a renewed prioritization of the study of subsidence in the state, leading to advancements in understanding that will have international benefit."~~

New paragraph (new parts in **BOLD**, deletions in ~~strikethrough~~):

(lines 1453-1464): **"A significant accomplishment in the historic period was not just mitigating the subsidence, but also the effort to study and understand it.** ~~In the historic that~~ period, the San Joaquin Valley subsidence was met by a concerted scientific effort that led to the development of the aquitard drainage model and the extensometer, key advances that have ~~continued~~ global importance **and impact** to this day (Gambolati & Teatini, 2021; Holzer, 1998). **Then, it was in part** the dramatic scale of the subsidence **that** provided ~~a major~~ impetus for the scientific research that allowed these advances to be made. **Today, the SGMA legislation marks a significant prioritization of groundwater in the Valley, and can lead to innovations in groundwater management and science.** ~~Here, we~~ **We hope that** quantifying the Valley-scale subsidence **one of our key findings -- that subsidence in the recent period has reached the same total volume as that of the historic period, over a shorter time -- brings increased visibility to the urgent need to catalyze a renewed prioritization of the study of subsidence in California."**

2. We split the paragraph that described how subsidence volume was estimated into two paragraphs. We made edits to clarify the methods used and reduce repetitions.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 180-186): ~~For the periods 2006-2010 and 2015-2022, we used existing InSAR datasets to calculate the Valley-wide subsidence volume. The 2006-2010 InSAR data were of poorer quality~~ **lack robust error quantification** so we **made estimates using all available InSAR datasets** ~~during~~ **spanning** that period, **and used the range of values to estimate uncertainty.** ~~and For that period, we calculated a single values for the Valley-wide subsidence volume rather than work at a finer temporal resolution. but the data during the 2015-2022 period have 6 daily resolution, so~~ **Much higher quality data, with rigorous error estimates, were available for the 2015-2022 period, and we used that resolution a single dataset at its raw temporal resolution (approximately 6-daily)** to estimate the Valley-wide subsidence volume **for that period.**

[NEW PARAGRAPH BREAK INSERTED]

(lines 188-200): The InSAR data map the spatial patterns of subsidence which, as shown in Figure 2b and noted by Faunt et al. (2016), reveal that subsidence was concentrated in two main areas, one centered on El Nido and the other on Corcoran, in both of ~~these~~ **the 2006-2010 and 2015-2022** periods. ~~To when generating our estimate of Valley-wide subsidence volume during the period 2011-2015, when InSAR data were unavailable, We used this information about the spatial patterns. For that period, the primary data that we used were~~ **subsidence measurements made at monitoring sites fitted with global navigation satellite systems (GNSS). These monitoring sites, illustrated by the black triangles in the maps in Figure 1b, provide a sub-cm-accuracy record of the vertical land motion over time, but they are few in number and are irregularly distributed** ~~but the station locations — illustrated by the black triangles in the maps in Figure 1b — are such that spatial resolution is limited. We used a geostatistical approach to interpolate between the GNSS stations, with the interpolation informed by the spatial subsidence patterns observed in 2007-2006-2010 and 2015-2022 and based on the assumption that subsidence was likely to have also been focused on the El Nido and Corcoran areas during 2011-2015...~~
[PARAGRAPH THEN CONTINUES WITH NEW CONTENT, SEE RESPONSE TO COMMENT 3.19]

We have also made minor changes.

Changes made to text (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~):
(line 171): ~~We~~ **To** quantified Valley-scale subsidence, **we used** the metric of Valley-wide subsidence volume.
(lines 160-164): The California government has directed over \$800 million to SGMA implementation activities as of 2023 (Petek, 2023), and a clear picture of the scale of subsidence, at the Valley-scale, can support the State in determining the appropriate level of investment **for** targeting subsidence mitigation.

(lines 164-170): The State government also adjudicates on whether local groundwater management actions are adequate, and Valley-scale subsidence information is important to ensure that fair standards are applied **across sub-basins**.

We moved the definition of the time period '2015-2022' to the end of paragraph 3, and clarified that the InSAR coverage does not end after 2022.

Changes to the text:

(lines 124-125): The two main periods with InSAR data are December 2006 - December 2010 (hereafter 2006-2010) and **post-May 2015** ~~to December 2022~~.

(lines 130-132): Specifically, we focus on the years 2006-2022, using existing InSAR data for the periods 2006-2010 and ~~2015-2022~~ **May 2015 to December 2022 (hereafter 2015-2022)** and developing new information for the period 2011-2015.

Finally, we switched the order in the final paragraph to better reflect the order of the paper. (colors show that the two pieces are swapped)

(lines 138-140; originally): In the discussion, **we compare this 2006-2022 record with that from the historic period**, and **consider the implications for groundwater management**.

(lines 209-211; new): In the discussion, we **consider the implications for groundwater management** and **compare our 2006-2022 record with that from the historic period**.

2.2 It is noted from Figure 1 that GNSS stations are sparse in severely subsiding areas, and the discussion section also points out that the interpolation of GNSS is the main source of error. How can the authors ensure that the interpolation results meet accuracy requirements? Can experimental internal validation results be provided?

We made three changes to address concerns about the validity of the GNSS interpolation:

1. We have added a new section, "Error estimation for 2011-2015", that describes a leave-one-out cross validation analysis to estimate the error in the interpolation.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 837-848): **The individual GNSS measurements we worked with for 2011-2015 record vertical motions with a high accuracy (~3 mm) (Farr & Liu, 2014), and measurement error is not expected to be a main source of uncertainty. Instead, it is anticipated that the main source of uncertainty will come from interpolating between sparse datapoints. To quantify this error, we applied a leave-one-out cross validation, repeating the kriging with each GNSS station left out and calculating the misfit between the station measurement and the interpolated map value at that station. The mean of these misfits was 0.09 m. This misfit was not spatially uniform, and to estimate the spatial dependence, we computed the standard deviation of**

the interpolated surfaces generated during the leave-one-out cross validation (Figure 7). We integrated the standard deviation across the entire Valley and used that value, which was 0.9 km³, as our estimate of the uncertainty in Valley-wide subsidence volume resulting from the sparseness of the GNSS stations.

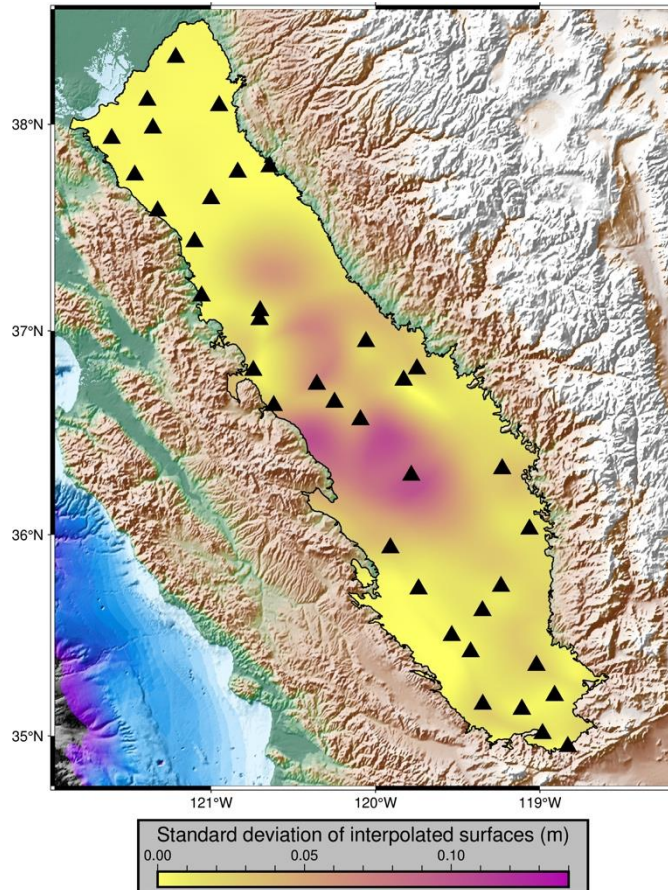
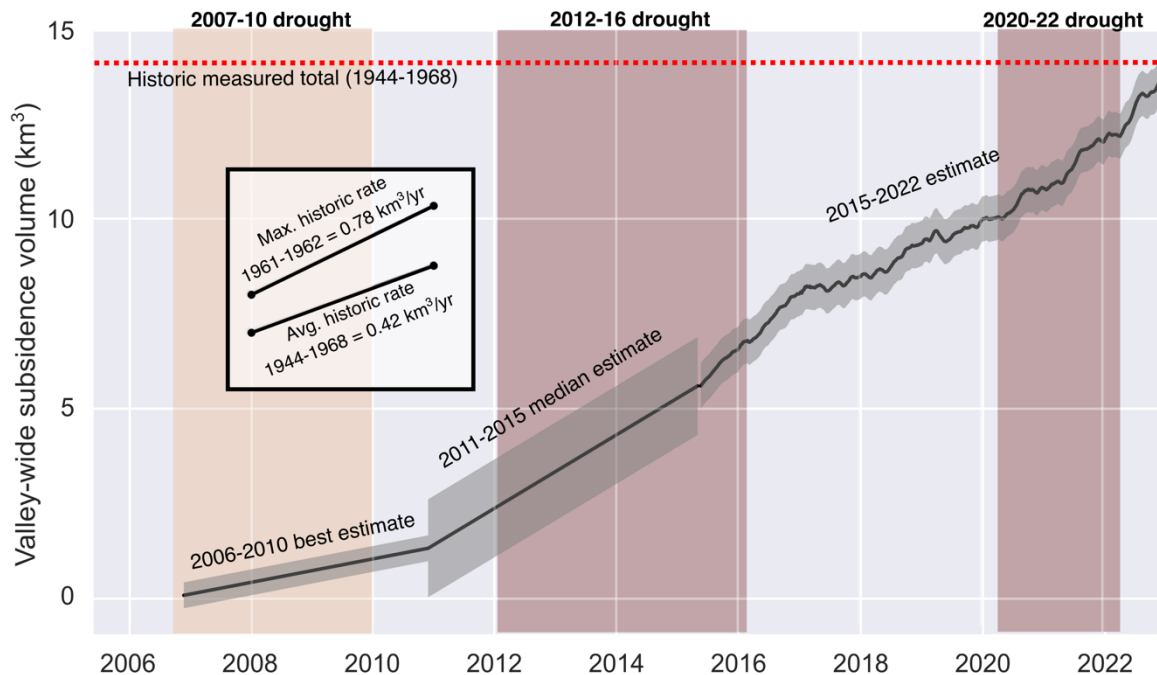


Figure 7 The standard deviation of all interpolated surfaces generated during the leave-one-out cross validation. The GNSS station locations are marked as black triangles.

2. We have included extensometer and levelling survey data for verification. This is described in the response to comment 3.19.
3. We updated Figure 8 (formerly Figure 6) with error envelopes and made changes to the text to introduce/explain those envelope.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
 (lines 855-872): The evolution of Valley-wide subsidence volume for 2006-2022 is presented in Figure 1. **The solid black lines represent our best estimate, with uncertainty bounds indicated by grey shading.** For 2006-2010, our best estimate is the constant rate that best fits the three individual estimates and the error is the mean misfit to those estimates. For 2011-2015, we used the median value derived from the five interpolated surfaces as our best estimate with an uncertainty of 1.3 km³, which is a conservative error estimate calculated by summing the

0.9 km³ and 0.4 km³ errors from bootstrapping and variation in correlation structures. For 2015-2022, we used the time series shown in Figure 2 as our best estimate and used the error analysis of Towill et al. (2023), who used subsidence measurements from independent GNSS station to quantify a pixel-wise error of 18 mm per measurement, equating to 0.6 km³ when integrated over the entire San Joaquin Valley, as the uncertainty.



*Figure 1 Summary figure showing the calculated time series of Valley-wide subsidence volume. The **black lines** shows the **estimates for 2006-2010, 2011-2015 and 2015-2022 periods, with the grey shading showing the estimated uncertainty for each period**. The red horizontal line represents the total from the historic period. The **white inset box shows the average and maximum historically-measured rates, calculated from data in Poland et al. (1975)**. Drought periods are marked with shading. See Methods 7 for a description of how the historic totals and rates were obtained.*

2.3 The article devotes a large portion to demonstrating how to calculate subsidence volumes from 2011 to 2015, with Figure 6 only showing the median estimate obtained during this period. Could detailed zoomed-in figures be provided?

We have expanded the error analysis as described in response to comment 2.2. This included an update to the Figure 6 (now Figure 7), so the uncertainty is now displayed with grey shading.

2.4 The supplementation of land subsidence data from 2011 to 2015 enables the continuity of land subsidence data in the region after 2007. However, regarding the theme of the article on managing record-breaking subsidence in California's San Joaquin Valley, could it be inferred based on existing subsidence data from 2007 to 2010 and 2015 to 2022 that subsidence is concentrated in the main areas of El Nido and Corcoran? Could related management recommendations also be proposed? Is it necessary to calculate subsidence data for the period 2011 to 2015?

We have added a new discussion section, “Historic context”. In the second paragraph of that section, we now clearly explain why quantifying 2011-2015 subsidence is important for subsidence mitigation.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1471-1482): **A significant accomplishment in the historic period was not just mitigating the subsidence, but also the effort to study and understand it.** In ~~the historic~~ **that** period, the San Joaquin Valley subsidence was met by a concerted scientific effort that led to the development of the aquitard drainage model and the extensometer, key advances that have ~~continued~~ **global importance and impact** to this day (Gambolati & Teatini, 2021; Holzer, 1998). **Then, it was in part** the dramatic scale of the subsidence **that** provided ~~a major~~ impetus for the scientific research that allowed these advances to be made. **Today, the SGMA legislation marks a significant prioritization of groundwater in the Valley, and can lead to innovations in groundwater management and science.** ~~Here, we~~ **We hope that** ~~quantifying the Valley-scale subsidence one of our key findings -- that subsidence in the recent period has reached the same total volume as that of the historic period, over a shorter time – brings increased visibility to the urgent need to catalyze a renewed prioritization of the study of subsidence in California~~

We also refer the reviewer to the 4th paragraph of the introduction, reproduced below, which discusses why our record is important.

“Why is such a record important for mitigating the subsidence? The legislative framework to tackle subsidence in California (the Sustainable Groundwater Management Act, “SGMA”) requires groundwater to be managed in such a way as to avoid six undesirable effects, one of which is “significant and unreasonable” subsidence (Dickinson, 2014). The California government has directed over \$800 million to SGMA implementation activities as of 2023 (Petek, 2023) , and a clear picture of the scale of subsidence, at the Valley-scale, can support the State in determining the appropriate level of investment targeting subsidence mitigation. The State government also adjudicates on whether local groundwater management actions are adequate, and Valley-scale subsidence information is important to ensure that fair standards are applied.”

2.5 The statement from lines 273 to 276 suggesting that subsidence details are not important to explain negligible interpolation errors might be too weak. How can the overall subsidence value be deemed reliable?

Regarding the error/uncertainty in the interpolated subsidence, see our response to comment 2.2. Regarding the importance of the details of the subsidence, and the size of interpolation errors (the statement that was formerly in lines 273-273): we have removed lines 273-273 and replaced them a more detailed/nuanced discussion of the 2011-2015 error. We also made a change at the point where the interpolation errors being small is first introduced.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 1056-1070): **Our error quantification for the 2011-2015 period revealed that there is significant uncertainty introduced by interpolating between sparsely distributed GNSS stations, as well as a smaller uncertainty due to potential variability in correlation parameters. However, the total error is still small compared to the Valley-wide subsidence volume for that period, and we consider our methodology an appropriate way to quantify the Valley-wide subsidence volume. The spatially-variable error indicates that our interpolated dataset may not be suitable for detailed local analysis, as there are many locations where the uncertainty exceeded 10 cm which will be unacceptable for many applications.**

(lines 765-769): The maps show subsidence concentrated in the two main areas centered on El Nido and Corcoran, ~~and produce subsidence patterns that are visually realistic,~~ **and there are only minor differences between the different correlation structures. This implies that variation in correlation structures is not a significant source of error in the interpolation.**

2.6 What is the basis for setting the parameters of the variogram in Method 4?

This is described in lines 1654-1658, repeated here:

“These parameters were chosen to ensure a satisfactory number of datapoints per lag (the number of datapoints per lag is shown in Supplemental Figures 1 and 2) while also giving good coverage of directions and distance. Note that the number of data in each direction is a function primarily of the Valley geometry, hence the high similarity between Supplemental Figures 1 and 2.”

2.7 What are the criteria for determining the effectiveness of the parameter fitting for the ellipse model in Method 4? Was cross-validation performed?

We have modified the text to clarify that we assess a good fit visually.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 1668-1673): To fit ellipses (defined by three parameters: azimuthal angle, major axis length and minor axis length) to the variograms, we started with an initial guess for the ellipse parameters, obtained by visual inspection of the experimental variograms. We then manually tweaked the parameters until a good fit, **determined by visual inspection**, was obtained. In determining a good fit, we placed particular emphasis on matching the model to the short-distance lags, as this is highlighted as good practice by Kitanidis (1997).”

2.8 What is the universal accuracy and applicability of the algorithm to fill in missing subsidence data? It can be further elaborated, because the vertical deformation accuracy of GNSS may be lower than that of insar data.

We have made several additions to the text that speak to this point.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 830-831, referring to accuracy of GNSS observations): **The individual GNSS measurements we worked with for 2011-2015 record vertical motions with a high accuracy (~3 mm) (Farr & Liu, 2014).**

- (lines 1083-1085, referring to global applicability): **We highlight the importance of independent deformation observations to facilitate the generation of high-quality InSAR datasets in any region of the world dealing with subsidence.**

2.9 The method of filling filling data gap has great significance in terms of data integrity, but what role can it play in understanding and preventing ground subsidence?

See response to comment 2.4.

Reviewer 3

Reviewer 3 made comments directly onto the manuscript using the Word “comment” facility. Those comments remain in the ‘track changes’ version, and the responses we provide here are duplicated there.

3.1 This is not extensively discussed and some of the inferences seem to be opinion and unsupported. I suggest changing the title. To something along the lines of what you say later is the aim of your study "The aim of this study is to develop a Valley-scale record, based on observations, of subsidence in that period. "

We have changed the title to better reflect the article contents.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1-2): ~~How to Manage~~ **Quantification of Record-Breaking Subsidence in California’s San Joaquin Valley Leads to Management Insights?**

3.2 From the title I expected to see how to manage subsidence. The abstract has one short sentence on how as the last sentence and even it is vague.

We have changed the title (see response to 3.1). We have also altered the abstract to emphasize that our management recommendations are high-level.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 20-23): Considering the **extraordinary** 2006-2022 **Valley-wide** subsidence ~~rate and the need to mitigate subsidence~~, **we make high-level recommendations for subsidence mitigation**, ~~we suggest highlighting the importance of focusing~~ groundwater overdraft **reductions** on the deeper aquifers where subsidence originates, and on localities where subsidence impacts are greatest.

3.3 Important to point out it might be the same magnitude, but the location has changed dramatically

Change not made. We agree that the changing location is an important point, but it is not a key focus of this paper so we do not highlight it. The additions of ‘Valley-wide’ and ‘high-level’ to the abstract (see response to 3.2) highlight that this study is about the insights gained from considering the total, Valley-scale problem.

3.4 Shouldn't you worry about just changing the location (particularly vertically) as much of the valley is semi-confined.

Change not made. Justification: The two changes are important and separate. There is insufficient resource to stop subsidence everywhere, so a) deep compacting aquifers must be targeted so the available resources are being used efficiently and b) the areas where subsidence is causing greatest impacts must be targeted so the greatest harm is reduced.

3.5 Also land use changes played a prominent role.

We have changed the text to mention this.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 38-41): However, following a series of droughts (2007-2009, 2012-2016 and 2020-2022) and the prioritization of water for environmental purposes, surface water imports have fallen **which, coupled with land-use changes, have led to** and renewed subsidence ~~has been observed~~ in the post-2006 period (Faunt et al., 2016).

3.6 Track to me sounds like a current or future measurement. The problem here is missing data and filling a data gap. Right?

We have changed the wording.

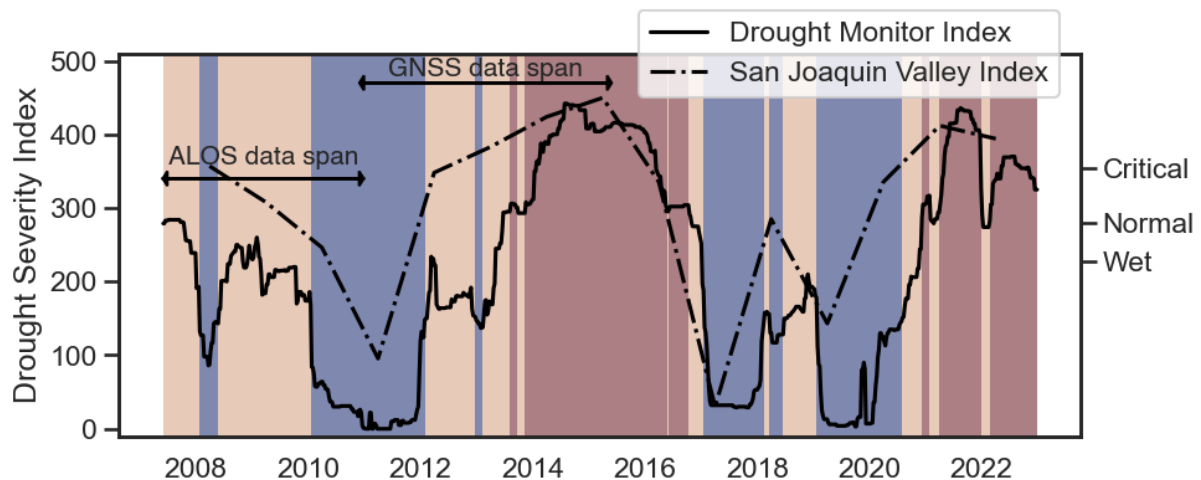
Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 116-118): Despite the severity of the problem, we do not currently have **a record of** ~~an ability to track~~ the Valley-wide subsidence over the full post-2006 period, meaning we lack the large-scale understanding of the problem required to support mitigation efforts.

3.7 How does this compare to the San Joaquin River index, which would be a more locally coincident indicator for this area?

It is very similar, although the SJR index changes more rapidly (the drought index contains some longer-term aspects like soil moisture which are absent in SJR index). We have added a brief discussion of the SJR index in Methods 5 and a new supplemental figure.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1698-1703) We considered the whole of the state because, although this study focuses on the San Joaquin Valley, the hydrology of the Valley is strongly influenced by conditions elsewhere in the state due to the high levels of water deliveries from elsewhere in the state. **We note that the San Joaquin River index, a more local index specific to the study area, showed very similar patterns (Supplemental Figure 1).**

Supplemental Figure 1:



3.8: Clarify if this is for SGMA overall or subsidence specific.

We have clarified this point.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
 (lines 160-162): The California government has directed over \$800 million to ~~supporting management~~ **SGMA implementation** activities as of 2023 (Petek, 2023)

3.9 Might also look up and include what federal government has spent on DMC and FKC as well.

We have added text earlier to highlight the cost of the canal repairs.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
 (lines 43-46): It has **necessitated multi-million dollar repairs** ~~reduced the capacity~~ of the gravity-driven canals and aqueducts that deliver water to the Valley and the major urban areas of southern California (Borchers & Carpenter, 2014; Jones et al., 2021; Sneed et al., 2018)...

3.10 State, specify.

We have made this specification.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
 (lines 164-169): The **State** government also adjudicates on whether local groundwater management actions are adequate, and Valley-scale subsidence information is important to ensure that fair standards are applied.

3.11 Since you are focusing on managing, you might bring up or discuss the historic effort that was somewhat related to reducing land subsidence, the federal (CVP) and state large aqueduct construction projects to move water to the western side of the valley to reduce subsidence and GW level decline (DMC and CV aqueduct).

We consider this comment to be very important. We decided to include the historic land subsidence reduction in an entirely new Discussion section, called “Historic Context”.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1452-1463): **A significant accomplishment in the historic period was not just mitigating the subsidence, but also the effort to study and understand it. In that period, the San Joaquin Valley subsidence was met by a concerted scientific effort that led to the development of the aquitard drainage model and the extensometer, key advances that have global importance and impact to this day (Gambolati & Teatini, 2021; Holzer, 1998). Then, it was in part the dramatic scale of the subsidence that provided impetus for the scientific research that allowed these advances to be made. Today, the SGMA legislation marks a significant prioritization of groundwater in the Valley, and can lead to innovations in groundwater management and science. We hope that one of our key findings – that subsidence in the recent period has reached the same total volume as that of the historic period, over a shorter time – brings increased visibility to the urgent need to study subsidence in California.**

3.12 Seems like this has already been occurring or started with SGMA.

We have reworded to acknowledge this point. (note, moved to “Historic Context” section)

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1460-1463): ~~We hope we hope that quantifying the Valley-scale subsidence in the state~~ **that one of our key findings -- that subsidence in the recent period has reached the same total volume as that of the historic period, over a shorter time -- may build on the SGMA legislation and catalyze a renewed prioritization of the study of subsidence in California**

3.13 Meaning the location of the sites is poorly known or there is poor distribution?

We have edited text to clarify it is the poor distribution.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 194-196): These monitoring sites, **illustrated by the black triangles in the maps in Figure 1b**, provide a sub-cm-accuracy record of the vertical land motion over time, but **they are few in number and are irregularly distributed** ~~are such that spatial resolution is limited.~~

3.14 Has anyone else calculated this to help compare to? Or could it be calculated by some of Sneed's work for at least good portions of the area to see if the number is reasonable compared to other studies?

We have expanded the analysis to compare with the two other Valley-wide estimates from the literature. This led to several changes in the text:

1. We now introduce and describe the calculation of subsidence volume for the three estimates, rather than one.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 180-186): ~~For the periods 2006-2010 and 2015-2022, we used existing InSAR datasets to calculate the Valley-wide subsidence volume. The 2006-2010 InSAR data were of poorer quality~~ **lack robust error quantification** so we **made estimates using all available InSAR datasets** during **spanning** that period, **and used the range of values to estimate uncertainty.** ~~and For that period, we calculated a single values for the Valley-wide subsidence volume rather than work at a finer temporal resolution. but the data during the 2015-2022 period have 6 daily resolution, so~~ **Much higher quality data, with rigorous error estimates, were available for the 2015-2022 period, and we used that resolution a single dataset at its raw temporal resolution (approximately 6-daily) to estimate the Valley-wide subsidence volume for that period.**

(lines 513-535): To obtain an estimate of the Valley-wide subsidence volume during ~~2007~~**2006-2010**, we used **the three published InSAR datasets that cover the whole valley for that period** ~~the InSAR dataset of Farr et al. (2015).~~ **Two of the datasets, those of Farr et al. (2015) and Ojha et al. (2018), used only data from the PALSAR ALOS satellite, while the third dataset, of Sneed et al. (2018), included data from both the ENVISAT and PALSAR ALOS satellites. The Ojha et al. (2018) dataset contained an average subsidence rate for the period, whereas the other datasets contained estimates of subsidence over shorter sub-intervals; following the approach of Lees et al. (2022) where ALOS data were also used but were considered too noisy to provide estimates of subsidence over smaller time periods, we used the total subsidence in all cases.** ~~The value~~ **We calculated the following Valley-wide subsidence vome estimates from the three datasets: was 4.8 1.2 km³ for January 2007 – December 2010 using the Farr et al. (2015) dataset was, 0.7 km³ for December 2006 – January 2010 using the Ojha et al. (2018) dataset, and 0.7 km³ for the January 2008 – January 2010 using the Sneed et al. (2018) dataset (Methods 1). To find a single estimate over the full 2006-2010 period, we found the constant subsidence rate that produced the minimum misfit with these three estimates, which gave a total of 1.2 km³.** ~~The full details of this calculation is provided in Methods 1.~~

(lines 1577-1599):

Ojha et al. (2018)

We downloaded the pixel-level December 2006 – January 2010 subsidence data from the repository at Ojha et al. (2022). We clipped the dataset to only the San Joaquin Valley, projected the average subsidence rates from satellite line-of-sight to vertical by assuming all motion was in the vertical direction and multiplied the pixel values by 3.1 to obtain values of total subsidence for December 2006 – January 2010. We then generated subsidence contours at the same subsidence values as in the Farr et al. (2015) dataset, and used the qGIS “add

geometry attributes” algorithm to calculate the area within each contour (QGIS Association, 2023). The area of each contour and corresponding subsidence volumes are reported in Supplemental Table 1. We rounded the final cumulative total of 0.69 km³ to 0.7 km³ to account for the approximations involved in the process.

Sneed et al. (2018)

First, we digitized the displacement contours of January 2008 – January 2010 subsidence from Figure 17 of Sneed et al. (2018). For calculating the Valley-wide subsidence volume, we worked directly with these contours, integrating within each contour to obtain the Valley-wide subsidence volume. We used the qGIS “add geometry attributes” algorithm to calculate the areas (QGIS Association, 2023). The area of each contour and corresponding subsidence volumes are reported in Supplemental Table 1. We rounded the final cumulative total of 0.73 km³ to 0.7 km³ to account for the approximations involved in the digitization process.

2. We now calculate the ‘best estimate’ for 2006-2010 as the estimate with minimum misfit to the three estimates, and discuss how considering three datasets improves our understanding of uncertainty.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 853-854): **For 2006-2010, our best estimate is the constant rate that best fits the three individual estimates and the error is the mean misfit to those estimates.**

(lines 1040-1057): Geodetic data allow us to take a Valley-scale view of subsidence by quantifying the Valley-wide subsidence volume. However, the estimates contain some error. **For the 2006-2010 InSAR-derived estimates, the sources of error relate to the quality of satellite measurements and steps taken during data processing (Jones et al., 2021). The 2006-2010 InSAR datasets are based on satellite measurements characterized by relatively long revisit times and long spatial baselines; both of these factors are expected to introduce some error. There is no formal error quantification associated with any of the 2006-2010 datasets used, and this is a feature common with InSAR datasets in the San Joaquin Valley from that period due to a lack of independent validation measurements available. The three datasets mostly use raw measurements from the ALOS PALSAR satellite, with Sneed et al. (2018) also including some data from the ENVISAT satellite. Different processing workflows were employed in each case, with Farr et al. (2015) using an “SBAS” methodology, Ojha et al. (2018) a wavelet-based method and Sneed et al. (2018) summing adjacent interferograms. Our error quantification for 2006-2010 is based on the variation between the three datasets, so primarily captures uncertainty stemming from different processing techniques rather than raw error in the satellite measurements, which are mostly common to the three datasets. It is likely that the true error, which could only be calculated if independent observations were available, would be larger.**

3. The Ojha et al. (2018) dataset started in December 2006, so we renamed 2007 -> 2006 throughout.
4. We incidentally discovered a bug in our code that led to the estimated volume for Farr et al. (2015) changing from 1.8 to 1.2 km³.

We chose not to include datasets covering subregions of the Valley, such as Smith et al. (2017) or Farr and Liu (2014), as: 1) the sub-regions are only a small portion of the total area, and 2) it goes beyond the scope of the present paper to explore in detail the differences between different InSAR datasets

3.15 This is a much higher rate, right? Maybe mention that or maybe its later.

See response to comment 3.20.

3.16: Seems like we always think of subsidence as downward, this might be more visually understandable with the y axis flipped and it might help to shade background with your droughts.

We decided to keep the figure in this orientation as that is consistent with how we have presented it throughout the paper, and with the Valley-wide subsidence volume curves originally done by Poland et al. (1975). We have added the drought shading from Figure 1.

3.17 Very cool and novel. Nice.

Thanks!

3.18 It wasn't released til recently, but it would be interesting, neither right nor wrong, to compare these numbers to CVHM2.

We consider this a very interesting suggestion, worthy of future work. We opt not to include the comparison here on the grounds that exploring the differences between simulated and monitored subsidence is a topic that deserves a paper all to itself.

3.19 I wonder if some of the extensometer data and surveying data could also be used to fill in these spatial gaps between GNSS data points. The extensometer isn't the whole column but could be used to estimate the fraction it correlated to where the data sets overlap. This might help with some of the uplift areas.

We have included extensometer and levelling survey data for verification.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
 (lines 200-206): **To validate our interpolated maps, we used data from levelling surveys and extensometers. The measurements from these methods do not directly record 2011-2015 subsidence, since the available levelling surveys span the periods 2009-2013 and 2013-2015, not 2011-2015, while extensometers measure subsidence to the depth of the instrument, and not the total subsidence. Nonetheless, these**

datasets were suitable for qualitative validation of our interpolations.

~~This allowed us to generate realistic subsidence maps for the 2011–2015 period from which we estimated the~~ We used the validated interpolated maps to estimate the **2011–2015** Valley-wide subsidence volume.

(lines 795–817): **We compared the interpolated maps to extensometer and levelling survey data, shown in the top two panels of Figure 6.**

(Extensometer measurements were scaled based on the instrument depth to approximate the total subsidence; see Methods 7 for a description of this scaling and details on the extensometer and leveling data used.) There is generally good correspondence, and we outline in Figure 6ii two places where both the interpolation and levelling measurements show higher levels of subsidence and two other areas where both showed lower levels of subsidence. The consistency between interpolated surface and measurements is further supported by considering the misfit between the two datasets, shown in Figures 6iii and iv. The mean misfit was relatively small, at 0.19 m. (Note that we would not expect the misfit to be zero even if the interpolation were perfect, as the extensometers and levelling surveys are measuring quantities that are related, but not exactly equal to, the 2006–2010 subsidence.) However, there were several areas where the interpolated deformation map showed uplift, and this was not supported by the measurements. We highlight the extensometers and levelling survey points where this occurred with red in Figure 6iii and iv. Since the observational data (GNSS and other) do not support the existence of anything other than minor and/or localized uplift, and subsidence theory predicts that the magnitude of any uplift from recharge effects will be many times smaller than that of the subsidence due to extraction (Galloway et al., 1999), we consider these areas of uplift interpolation artefacts. On this basis, we set the subsidence value in any areas of uplift to zero. We used these final maps, with uplift set to zero, to calculate the Valley-wide subsidence volume, giving values for the 2011–2015 Valley-wide subsidence volume between 4.2 – 4.6 km³ (i.e. the estimate has an associated uncertainty of 0.4 km³).

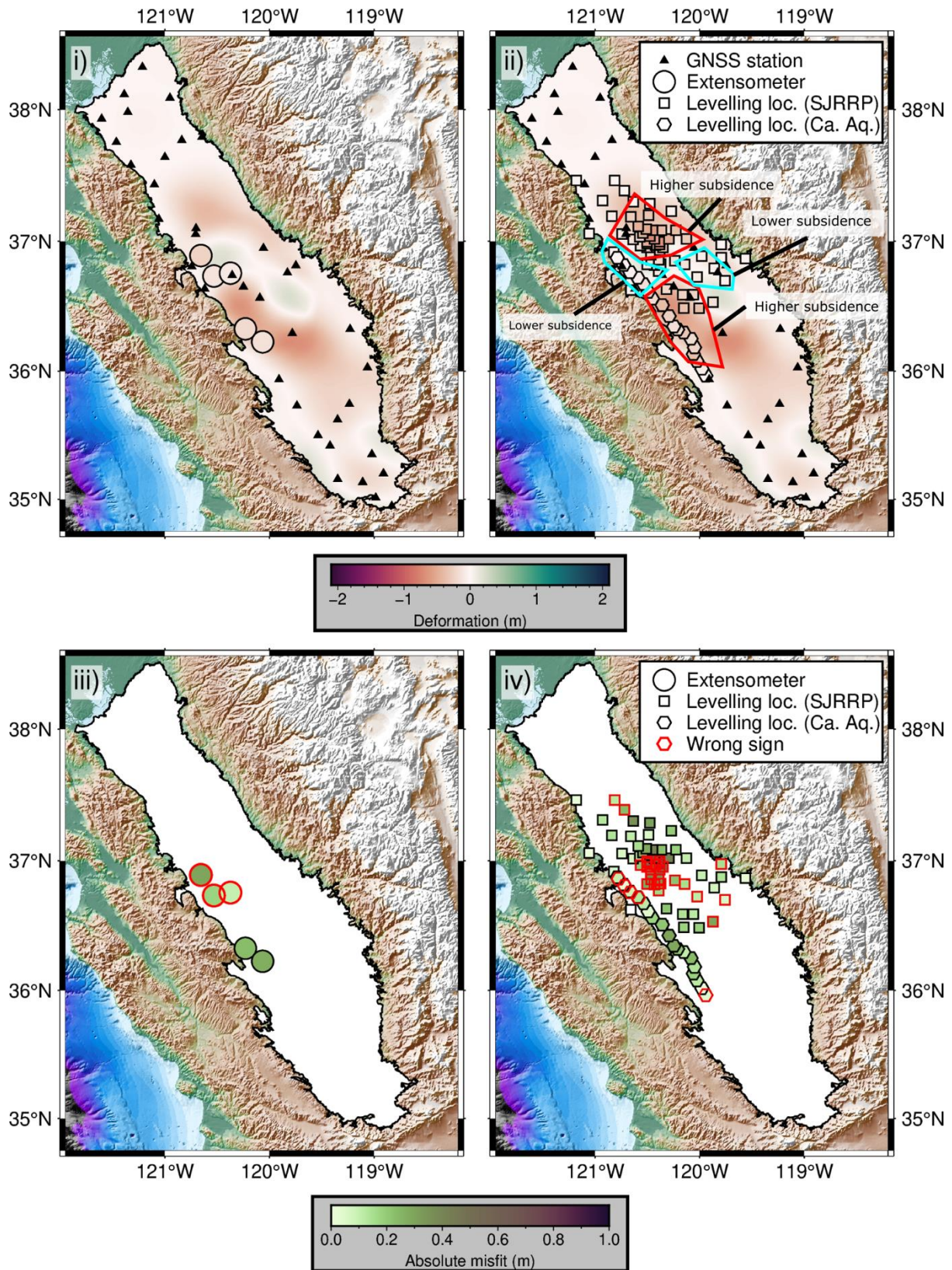


Figure 6 The top two plots show the deformation estimates from i) extensometers and ii) levelling surveys alongside the interpolated 2011-2015 deformation. GNSS station locations are also plotted. The bottom row shows the absolute misfit between the interpolated 2011-2015 subsidence and i) extensometer and ii) levelling survey measurements. Locations where the interpolated map showed uplift and the observations showed subsidence are outlined in red. In i and ii, the interpolated 2011-2015 subsidence showed is that created using the first correlation structure (the topmost ellipse in Figure 4). Two different levelling surveys are shown – those represented by squares come from the San Joaquin River Restoration Partners Geodetic Control Network and those represented by hexagons are from the monitoring program along the California Aqueduct.

(lines 1768 – 1817): **Methods 7: Processing leveling survey and extensometer data**

Extensometer data

We first collated information on all extensometers in the San Joaquin Valley. Information on extensometers was sourced from: 1) the USGS's California Water Science Center (https://ca.water.usgs.gov/land_subsidence/central-valley_extensometer-data.xlsx), 2) Faunt (2012), and 3) Poland et al. (1975). From this information, we then identified the five extensometers for which measurements were made for the full 2011-2015 period. These five extensometers were all operated by the USGS, and we used the measurements as available at https://ca.water.usgs.gov/land_subsidence/central-valley_extensometer-data.xlsx. (The data can also be found tabulated at Faunt et al., 2023). To convert the measured compaction over the extensometer depth interval (c_{meas}) into total subsidence, we used the empirical relationship between the extensometer depth (d) and the percentage of total subsidence recorded (pc_{tot}) developed by Ireland et al. (1984), which is reproduced below:

$$pc_{tot} = 133 \log_{10}(d) - 341$$

where it is noted that depth in the above equation is in units of feet, not meters. From this relationship, the total subsidence (s_{tot}) at a given extensometer can be estimated as:

$$s_{tot} = \frac{pc_{tot}}{100} * c_{meas}$$

The estimate of total subsidence obtained using this method is only approximate, since it relies on an empirical relationship from the historic period that may have altered for the recent period, and the r^2 value for the relationship was reported by Ireland et al. (1984) to be relatively low, at 0.76. However, it was sufficient for our purpose of comparing general patterns of subsidence.

Leveling data

Details on the available leveling surveys in the San Joaquin Valley is provided in the Supplemental Material of Faunt et al. (2024). Of the available surveys, two contain information on the 2011-2015 period: the San Joaquin River Restoration Partners Geodetic Control Network, operated by the Bureau of Restoration; and the monitoring program along the California Aqueduct, undertaken by California Department of Water Resources. Various other programs of leveling surveys have operated in the San Joaquin Valley, but these did not cover the relevant 2011-2015 period.

The leveling survey measurements plotted in Figure 6 were downloaded from Faunt et al. (2023). We show the measured subsidence at survey points between July 2012 and July 2015 from the San Joaquin River

Restoration Partners Geodetic Control Network and the measured subsidence between June 2009 and February 2015 along the California Aqueduct. The measurements are plotted directly (unscaled) in Figure 6. For the California Aqueduct, only every 5th point is plotted because the raw measurements are spaced approximately 50 m apart which was too spatially dense for visual display.

3.20 Historic total and historic rate. Are these the same time period and is it for 1925-1970? Might remind us if so. Is it a coincidence it's the same amount? And if so the rate is higher, right, same amount over much shorter period. Scary.

We added additional labels to Figure 6 (now Figure 8) that now make the timespans for the historic total/rates clearer. Yes, it is a coincidence that it's the same amount, and it is a higher rate over a much shorter period. We have made changes to the text to a) make the historic labels clearer and b) emphasize the higher rate over shorter period:

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 880-882): Figure 8 **also shows** the maximum and average rates of **Valley-wide subsidence volume** during the historic period, **as well as the 1944-1968 total (the 24-years within the historic period for which records are available).**

(lines 303-306): Comparing to the total measured during the historic period, **we find** ~~it can be seen~~ that the Valley-wide subsidence volume in the 16 years between December 2006 and December 2022 matched the total that occurred during 1944-1968 (the 24-years within the historic period for which records are available).

3.21 Reference? And also time periods over which these are and do they represent droughts?

The figure has been updated to make this clearer and we have included the reference in the caption. Note that more detail is provided in Methods 8.

3.22 Maybe I am misunderstanding, but I don't see how you make the jump that yours is 10%. Didn't you adjust your estimates for the GNSS data for the 2007-2010 estimate and therefore reduce some of this error?

We have removed this reference. Instead, we have a much more detailed discussion of InSAR errors that follows from the inclusion of three datasets for 2006-2010. See response to comment 3.14.

3.23 This could be better quantified by looking at extensometer data and surveying data that are available for some sites between for at least verification/validation of your estimates if not improving the overall kriging as input data.

We have included the extensometer and survey data for visual/qualitative check - see response to comment 3.19. Additionally, we have introduced a cross-validation process to estimate the error – see response to comment 2.2.

3.24 I think this is somewhat true, but also an over simplification. Recharge areas are often the areas that have some of the pore space draining and the act of getting water in the recharge area can does induce a pressure response that goes toward mitigating subsidence.

We agree with the reviewer and have removed this statement. We also re-clarify this point/idea later.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 1247): ~~The current practices of managed recharge are not targeting~~

Where in the aquifer system are the compacting aquifers?

(lines 1345-1346): **The key point, which we emphasize, is that overdraft reductions in the deep aquifers are required if we are to significantly reduce** subsidence.

3.25 They still have a recharge source and a pressure source that can be way away from the locations of the subsidence.

We agree with the reviewer's comment. This paragraph has now been softened, but we made modifications to the following paragraph to include the point about a possible distant pressure source.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)

(lines 1253-1325): **At these depths**, ~~it is the excessive pumping and resulting overdraft in the deeper aquifers that causes the compaction, where~~ the presence of numerous clay interbeds create the conditions for compaction – hydraulic isolation from the water table, and compressible clays.

(lines 1337-1343): A third approach is to ~~raise the water table in locations that are known to directly recharge the deep aquifers through connected pathways~~ **recharge the shallow aquifers, currently the most common approach to recharge. But for this to reduce the subsidence-causing overdraft in the deep aquifers, raising the water table recharge needs to occur** in locations that are known to directly recharge the deep aquifers through connected pathways. **This might require shallow recharge not in the location of the subsidence, but in a more distant, but hydraulically connected, location; this would require coordination across sub-basins.**

3.26 Looking at more recent GNSS and extensometer data in various locations the amount , type, and part of the aquifer compacting varies quite significantly in different areas of the valley. Some areas have a substantial component of delayed subsidence while others are more instantaneous. This is an important point to consider and bring out in this discussion.

Two comments: 1) We think the majority of evidence points towards a deep origin for subsidence, especially in areas where the largest subsidence rates are occurring. In slower-deforming areas, there may be more elastic deformation, and in those areas a larger percentage of the total may be occurring in the shallow aquifer. However, these areas are not those of most concern.

2) Delayed/deferred subsidence is important, but not a focus of our study.

Regarding these points, we have added the Sneed et al. (2018) reference to provide more evidence of deep, recent subsidence plus added a few words to highlight that we are referring to the rapidly subsiding areas. However, we have not otherwise altered the manuscript.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~) (lines 1247-1253): Based on extensometer observations **in the historic period**, Ireland et al. (1984) found compaction to increase logarithmically with depth, with only 20% of compaction occurring in the first 150 m but 60% in the first 300 m. ~~while the recent numerical modelling from Lees et al. (2022) found that 90 % of compaction between 1997-2017 occurred deeper than 110 m.~~ **For the recent period, there are fewer available observations, but both data (e.g. Sneed et al., 2018, reporting on the Fordel extensometer) and modeling (e.g. Lees et al., 2022, considering a different site in the Valley) suggest that the greatest** compaction is occurring in the deeper aquifers of the San Joaquin Valley. ~~There is a growing consensus that compaction is primarily occurring in the deeper parts of the aquifer system in the San Joaquin Valley~~

3.27 As mentioned earlier this may not be all bad if it is a connected recharge area. Pressure plays an important spatial component to this. I think you need to back some of this up by calculations as opposed to generalizations.

We agree with the reviewer's comment and have clarified this sentence by making it clear we are referring to the situation where shallow recharge is incentivized without any regard to interconnected pathways to the deeper aquifers.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~) (lines 1346-1349): **At present, there are instances where** growers are given credit for the water added to the shallow aquifers and allowed to increase the pumping of the deeper aquifers **without any means of ensuring that the shallow recharge is benefitting the deeper aquifers.**

3.28 I don't think you have proven this by this paragraph. Maybe soften this to say its not the only way and more quicker and localized alternatives should and could be considered.

We agree that this statement was overly strong. We have replaced it with a softer and more specific recommendation.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~) (lines 1325-1327): ~~Recharge of shallow aquifers is not the optimal way to mitigate subsidence.~~ **It is therefore important that, when aiming to achieve subsidence mitigation, overdraft reductions are targeted to the deeper parts of the aquifer system.**

3.29 This may work well in some areas and not others. Based on AEM and drillers logs, and examining groundwater levels it is evident that there are many fine-grained layers in a lot of the system that semi-confine and may keep this from working as effectively as may be thought.

Although we agree with the reviewer that the effectiveness will vary with location, there is not evidence to indicate that shallow aquifers produce significant amounts of compaction. We have tweaked the sentence to acknowledge that it may not be a good approach everywhere.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1330-1333): Given that most of the pumping is to support irrigation for agriculture, could a commitment be made **in some areas** to managing the shallow aquifers as the water source for irrigation – both recharging and pumping from shallow depths?

3.30 This is being done and has been done for quite awhile in and around Sacramento and Stockton, I think.

We found a reference supporting the reviewer's statement and have added this.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1334-1336): **While this practice has been introduced in certain areas of the Sacramento Valley (Spencer & Greenspan, 2023)**, it is rare in the San Joaquin Valley due to the legal requirement to treat injected water to drinking water standards.

3.31 (lines 355-359): Above you really discounted this, please check for consistency. I actually think this angle on this is a bit more real other than the time, space, and pressure issue commented on separately.

We have softened the earlier statements that discounted this (see response to comment 3.24). We have also added nuance to the description here, speaking more about the locations of shallow recharge and the need for coordination (see response to comment 3.25).

3.32 The actual physical moving of particles may take a long time, but the pressure connections and responses can reach great distances and be relatively rapid.

We reviewed the literature and do not find consensus on how long these pressure connections take. Probably, it is no more than a couple of years. We have not modified the manuscript.

3.33 These are very different animals for one sentence.

We have removed this sentence. Instead, we provide a more balanced summary of our recommendations for groundwater management policies in lines 1351-1353:

“Groundwater management policies that successfully reduce subsidence will be those that show awareness of the importance of the deep, compacting aquifers.”

3.34 Not sure they increase efficiency, but do help address.

We have rephrased this sentence.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1355-1356): While the above strategies will ~~increase the efficiency of~~
~~subsidence mitigation~~ **be effective in helping to address subsidence**, we
consider it unlikely that they will reach the 0.90 km³ yr⁻¹ required to halt
subsidence everywhere.

3.35 How do you define this? By dollar amount of damage or who is affected or
reduction of storage that might impact a local user? Or how does flooding areas and
impact from that come in?

We have provided some more detail here. However, as described in sentences that
follow, one of our recommendations is that more effort should be spent quantifying
the multi-faceted damaging impacts of subsidence so communities can decide what
their priorities are.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1357-1358): Therefore, we also recommend that overdraft reductions
for subsidence mitigation target the places where the **subsidence will cause**
the greatest social and/or economic costs.

3.36 To me this is a stretch to go from the magnitude (and location) that is required
to a basis for effective mitigation. I think the most novel and well researched and
conducted part of this study is the calculation of the magnitude and developing a way
to spatially and temporally map, with a novel way at filling in gaps in data.

We agree that the previous statement was a stretch and have watered it down for
this revised version.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1477 – 1478): ~~We have shown that such a~~ **This** quantification can form
~~a basis for developing effective subsidence mitigation by providing an~~
~~understanding of~~ **provides an understanding of** the magnitude of overdraft
reduction that is required.

3.37 Really be careful of this term. It's the pressure response that needs to get there
not the physical particles.

We have changed from 'reach' to 'target'. We have also modified this line to – in line
with previous comments – clarify and soften our recommendation.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1478-1480): Our results motivate us to advocate for the increased
adoption **of** overdraft reduction ~~through managed recharge~~ that ~~reach~~ targets
the deeper aquifers.

3.38 Very important point and I think the first time it is really brought up. Might
expand on this and the fact that recharge maybe further from an extraction point that
is hydraulically connected may be more effective at reducing some subsidence (with

some time) than some local changes. This will take education and be harder for some of the local management to grapple with.

We have included the idea of recharge at distance from an extraction point, and the need for coordination across sub-basins; see response to comment 3.25.

3.39 Were there any that could help constrain your uplift places even though they are not complete data sets?

This is a good suggestion. However, instead of following this approach, we included extensometers/levelling surveys; see response to comment 3.19.

3.40 Wouldn't anisotropy affect this and maybe 60km one direction be very different than another?

Yes, we generally do not think that inverse distance weighting is a good approach. There are not enough stations to deal with anisotropy using additional data – and this is why we used a variogram approach.

3.41 Seems worth at least looking at DWR's San Joaquin River index which would closer match this area and not be affected by droughts in northern and southern parts of the state that are different in scope. I suspect this is really close though.

See response to comment 3.7.

3.42 This is very vague.

We have added some additional detail.

Changes made to text: (insertions in **BOLD** and deletions in ~~STRIKETHROUGH~~)
(lines 1765-1766): We then exported the output as a csv file and **reformatted it into grids which could be readily plotted and analyzed using**
~~interpreted it within~~ Python.

3.43 Why not use the graph he compiled for cumulative totals in figure 6?

We opted not to do this because we felt it make Figure 6 too busy.

General changes not specific to any reviewer

- The paper was originally submitted to a format with a stricter word-count limit. Taking advantage of more available words in the current journal, we have modified the abstract slightly to aid readability. There has been no alteration to meaning.

Changes to the text:

(lines 13-16): ~~Although subsidence is~~ **The impacts of the subsidence are severe, with** ~~modifying modified flood risks, damaging damaged aqueducts, and permanently altered altering aquifer dynamics., the~~
However, we do not have a complete record of the post-2006 subsidence ~~is incomplete~~ due to a 2011-2015 gap in Valley-wide observations, and **this makes it** difficult to develop an appropriate management response.

(lines 17-20): Here, we used satellite geodetic subsidence measurements to quantify the Valley-wide subsidence volume during ~~the 16-year period~~ 2006-2022. We found a total subsidence volume of 14 km³ **over the 16 years**, the same as was measured during 24 years of monitoring in the historic period

- Due to a small coding bug that was spotted, the interpolated deformation shown in Figure 5 has changed slightly, and the range of correspond Valley-wide subsidence volume estimations have changed from 4.15 – 4.23 km³ to 4.2 – 4.6 km³.
- The above coding error led to minor changes in the subsidence time series in Figure 8 (old Figure 6). The subsidence rate is now approximately constant from 2011-2017 whereas before it increased from 2016-2017.

Changes to the text:

(lines 869-871): Our results reveal how there was a relatively small amount of subsidence during 2006-2010, which was followed by a larger subsidence volume during the 2011-2015 period that **continued to 2017** ~~accelerated in 2016~~.

- The above coding error, and changes to the 2006-2011 period, led to a slight change in the Valley-wide subsidence volume rate from 2006-2022. It is now 0.84 km³ yr⁻¹ compared to 0.89 km³ yr⁻¹ in the previous version. This also changed the percentages in line 1228 from 39-42 to 36-39.
- Minor changes were made to the appearance of Figure 8 (formerly Figure 6): a solid black line is now used for all the ‘best estimates’ and a thicker red dashed line is used for the historic measured total.
- We added a new short summary statement to take stock of the changes made to the section “Accuracy of Valley-wide subsidence volume estimates”

Changes to the text:

(lines 1081-1083): **Overall, although there are substantial errors present, the errors remain small compared with the total subsidence volumes, and** geodetic data therefore seem an appropriate tool for estimating Valley-wide subsidence volume.

- We included two additional phrases in the first paragraph to provide the reader with a sense of the scale of subsidence.

Changes to the text:

(lines 32-35): During this period, 11000 km² of the Valley sank by over 30 cm **and total subsidence locally reached 9 m**, an event described as “one of the single largest alterations of the land surface attributed to humankind”

(lines 38-41): However, following a series of droughts (2007-2009, 2012-2016 and 2020-2022) and the prioritization of water for environmental purposes, surface water imports have fallen which, coupled with land-use changes, have led to renewed subsidence in the post-2006 period, **when rates have locally exceeded 30 cm/yr** (Faunt et al, 2016).

- We have occasionally replaced ‘aquifer system’ with ‘aquifers’, to make sure that we are using consistent terminology throughout the paper.
- We altered Methods 6 to note that we used nested structures (this was already in the main text but was missing from the methods)

Changes to the text:

(lines 1760-1763): **For both nested structures**, ~~We~~ specified the major axis length, minor axis length and azimuth in the ordinary kriging algorithm within the software, with a minimum and maximum number of conditioning values set to be one and thirty respectively.

- Typos/very minor changes:

(lines 1211-1213): Overdraft results in a reduction in the volume of stored water in the aquifer system (commonly referred to as **a reduction in storage**) equal to the amount of overdraft.

(lines 740-741): When compared with the subsidence maps in Figure 1, the subsidence in this interpolated map **is** spatially diffuse ~~subsidence pattern~~

(lines 1224-1226): (The expansion of water represents a third physical process, but – as shown by Williamson et al. (1989) -- this is a negligible ~~source of water~~ in the San Joaquin Valley.)

(line 1572): (see ~~online~~ Methods 5)

Author responses

This document details the final changes made in response to reviewer comments, and any other changes made. Excluded are changes made in response to editorial comments, which are documented separately in the Editorial Requests Table.

Reviewer #2 (Remarks to the Author):

My concerns have been well addressed by the authors. I would like to suggest accepting for publication.

- *No changes made.*

Reviewer #3 (Remarks to the Author):

This paper develops a method to quantify recent subsidence volumes in the San Joaquin Valley post 2006. To date, only numerical Hydrological models, spot measurements, and incomplete satellite measurements have been available. This quantification of subsidence post 2006 is useful for regional insights into groundwater and subsidence management. These subsidence volume rates could be used to help validate rates from numerical groundwater flow models. I think it is important to point out that although the rate has gone up, the locations of subsidence have changed (at least in some places and particularly the old maximum location).

The paper should influence managers to think more strategically in terms of subsidence management. In terms of management, the article effectively articulates that the subsidence historically and recently has been in the deeper parts of the system. The management technique suggested to move more pumping to the shallower system should be an effective approach in hydrogeologically acceptable locations, but managers should proceed cautiously and monitor this part of the system. There is limited evidence that some subsidence is beginning to occur in shallower parts of the system as the pumping is moved to shallower parts of the system.

Notes (not needed to be included in review):

Check caption figure 1, first reference to InSAR coverage is 2006-2010 and rest are 2007-2010. Please check.

- *Figure 1 caption slightly altered for clarity.*

Lines 379-383 include a reference to a model for overdraft rates (Brust et al., 2013). Seems like for completion it would be good to include Faunt et al. (2024) which has a similar, though slightly higher rate.

- *Added Faunt et al. (2024) reference as suggested.*

Lines 414-216 Are an oversimplification that does not take into consideration that during these periods the vast majority of pumping where finer grained materials were present was in these deeper parts of the aquifer. IF pumping moves to the shallower parts of the system that are semi-confined to confined, then these shallow parts of the aquifer are also likely to have subsidence. You don't want to get rid of one problem and create another. This should at least be mentioned here. I know later it is alluded to.

- *Added a one-liner to mention that clay-rich conditions can exist in shallow aquifers, plus a very small rewording to add clarity.*

Lines 423-425 The geology is also much finer grained possibly making this injection less effective and also deeper than the Sacramento area.

- *We have added reference to the greater aquifer depths.*

Lines 435-438 A reference as to information on growers' credits would be useful.

- *Change not made.*

Changes not specific to reviewers

A small error was fixed in the code that generated Figure 5. This change has knock-on to Figures 6 and 8, and further meant that the range of subsidence volumes has changed from 4.2-4.6 to be 4.1-4.3 km³. We have altered the relevant figures and the parts of the text that referred to the 4.2-4.6 km³. This does not alter the manuscript's findings or the thread of the manuscript's argument.

We made some minor changes to wording throughout, which do not change the substance or meaning. These are not listed here but are all marked in the 'track changes' version. Other changes: we added the labels showing "Corcoran" and "El Nido" to Figure 7 and corrected a typo in Figure 4 (2007 should have read 2006).