Response to Anonymous Referee #1

Thanks for the comments. I believe the suggestions will increase the clarity of the report. I've provided author responses (AR) below each Referee comment (RC).

My updated comments/responses are in red, these are changes I made or did not make that differ from what I previously indicated in my response to the referee's comments (currently posted online). Unless otherwise noted, I completed the revisions I indicated in my response to the referee's comments.

Incorporating the referees' suggestions lengthened the manuscript. To address this issue, I also went back through the manuscript and removed nonessential information and references in an attempt to shorten the overall length of the report.

Major comments Methodology

RC1: Pg. 5, ln. 13-14: Here you explain how "daily concentrations are flow normalized (FN) to remove the influence of year-to-year variability from stream…". However, the manuscript focuses on exploring potential drivers grouped into two general categories: (1) land use/management changes, and (2) streamflow regime. I am a bit confused as to how you normalize / remove the effects of flow, but at the same time attribute the changes in stream sediment to "streamflow regime". Can this be clarified?

AR1: The flow normalization (FN) process removes the effects of year-to-year variability in streamflow but still retains the influence of systematic or progressive changes in magnitude, frequency or duration of flows over time (aka changes in the "flow regime"). All rivers have a characteristic flow regime that captures the "typical" temporal patterns of high and low flows across a year. With a stationary flow regime, some years will have higher (or lower) flows than other years due to variable weather, but this year-to-year variability in the magnitude, frequency or duration of flows remains within the expended range for the given river. For example, one year might have a higher spring flood than the next year, but this variability is expected and captured in the river's "flow regime". This is the "year-to-year" variability that is being removed during the FN process. However, nonstationary conditions lead to some (or many) parts of the flow regime to shift over time. For example, high flows may become higher or more frequent over time. This variability is a systematic change streamflow and a fundamental shift in the flow regime. The effects of these systematic changes in streamflow on water quality are still retained in the FN process, whereas the effects of year-to-year variability in streamflow are removed. Another way to think about it is that the FN process attempts to remove the "noise" introduced from variable climate (year-to-year, non-systematic, variability) but still capture effect of the "signal" from any systematic changes in streamflow on water quality. I will add text to the introduction and methods to clarify the difference between "year-to-year" variability in streamflow (noise) and systematic changes in streamflow magnitude, timing and frequency (signal) and why parsing out these types of variability help us better understanding changes water quality. Thanks for noting this point of confusion.

RC2: Similarly, on Pg. 6, ln 30 to 31 you give citations on how you "parse water-quality trends into the streamflow trend component (QTC) and management trend component (MTC)." Although, I agree that

citations are a convenient way to cite methodologies, I believe that most of the results and conclusions are based on this "parsing" method. Therefore, it would be important to see explicitly how methods from Choquette et al. (2019), Hirsch et al. (2018a) and Murphy and Sprague (2019) were combined, modified, and used to arrive at the QTC and MTC values. I think the current length of the manuscript is good. Therefore, this should be included in the supporting information. I believe this will make the work presented in this manuscript more transparent for future readers, rather than trying to mix and match methods from three different sources. One can then better understand how these methods were applied in this manuscript and judge whether the presented results make sense.

AR2: While was writing, I was unsure about how much "background" (previously published) method information to include in the manuscript. Based on this feedback, I see that elaborating more fully on the methods will help a reader better understand the process. I will add a section to the Supporting Information that more clearly describes how the various methods from Hirsch et al. (2018a), Choquette et al. (2019) and Murphy and Sprague (2019) all fit together.

RC3: Pg. 5, ln 23-24: "…to gauge the uncertainty of the trends, likelihood estimates of the trend direction for each site and parameter were extracted from Murphy et al. (2018)". I tried to find how this was calculated by looking up this reference. However, this appears to be a USGS dataset which points at yet another set of citations for methods. I believe the citation for the calculation of likelihood is from Oelsner et al. (2017). However, Oelsner et al. (2017) calculates a number of things. Similar to the comment above, I think the supporting information should include a section where the author lists the equations used for the most critical calculations being made (the ones the support the figures, results, and conclusions). The citations can and should still be in the manuscript. However, they are a poor substitute for trying to understand the statistical methods that were used in this manuscript. I think a short appendix where the author provides the reader with the methods used could help the reader identify the necessary methods to recreate the results presented in this manuscript.

AR3: Good point. The appropriate reference for the uncertainty analysis is Hirsch et al. (2015), which was implemented using an updated R package (Hirsch et al. (2018b)). I can see how providing more detailed information in the Supporting Information would help a reader better understand these method details. I will add this, along with the other method information mentioned in a previous comment, to the Supporting Information. Furthermore, I will clarify in the main body of the text the primary reference for the uncertainty analysis methods.

RC4: Pg. 5, ln 10-29. Just curious as to why the author did not use Ryberg et al. (2013)'s SEAWAVE-Q method to separate seasonality and streamflow from the sediment concentration data? This is an available method from the USGS, so I expected it would be popular amongst other USGSers. Is WRTDS superior to SEAWAVE-Q for some reason? Furthermore, it would be important to cite Sullivan et al. (2009)'s contribution to your introduction (pg 2., ln 9-26) who compared various statistical methods for trend detection.

AR4: SEAWAVE-Q was designed for determining pesticide trends. The shape of the seasonal variability of pesticide concentrations in rivers is not well modeled using a sin/cosine function, which is the typical approach used in most efforts to model trends with regression equations. SEAWAVE-Q was built to better model this distinct pattern. WRTDS is, arguably, a better model for other water quality parameters such as nutrients, major ions and sediment. Additionally, WRTDS provides features that SEAWAVE-Q does not, such as flow normalization and a more flexible model fit that allows for variation in the relationships between concentration and season, time, and flow. Furthermore, WRTDS allows for the parsing of concentration trends into other "components of change", a feature not available in SEAWAVE-Q. As an aside, the trend results presented in this manuscript are from a national-scale effort (documented in Oelsner et al., 2017) and as part of that effort we also determined pesticide trends and used SEAWAVE-Q for those analyses.

At this point, I respectfully decline the suggestion to discuss various methods for trend detection in the Introduction. Currently, the introduction focuses on methods for understanding trends and exploring potential causes. It does not cover various methods for trend detection. There are other good papers out there that explore this topic, Sullivan et al. (2009) being one of them.

Cluster of increasing sediment in NW US

RC5: Pg. 1, ln. 1, title: "Declining suspended sediment in US rivers and streams" – How about the northwest coast TSS cluster that is showing a clear increase in suspended sediment. A more accurate title would be "Changing suspended sediment in United States rivers and streams...".

AR5: Good point. I will update accordingly.

RC6: Pg. 8, ln 13-16. Discussions about the TSS trends in northwestern US seem to need a better explanation. One reason that comes to mind is deforestation, which is arguably one of the largest contributors (in terms of land use change) to suspended sediment concentrations in rivers. A quick search on Global Forest Watch (https://www.globalforestwatch.org/) shows that there has been a decrease in tree cover in the states of Washington and Oregon since 2000. Perhaps there is a correlation between the decrease in tree cover and increase in suspended sediment concentration.

AR6: Agreed. Adding more discussion focused on the increasing TSS cluster in the NW US would strengthen the report. Currently, this topic is given only cursory attention. However, this portion of the text (section 3.1) focuses on presenting the trend results and broad insights from geographic cluster and land use. Thus, I plan to add a discussion of the TSS cluster in the NW US to the "Land management changes" section (section 3.2) or the "Importance of location section (section 3.4) of the manuscript.

I did not include deforestation in the correlation analysis because temporally consistent estimates of forest cover and timber harvesting are not available back to 1992. To my knowledge the earliest spatially and temporally consistent data on forest cover begins in 2001 (https://www.mrlc.gov/national-land-cover-database-nlcd-2016) and timber begins in 1999

(https://pubs.er.usgs.gov/publication/ds948). However, I agree that even without a temporal perspective equivalent to the other variables in table 1, this is still plenty of opportunity to bring in some quantitative information about forest and timber changes and relate them to changes in sediment. To that end, I plan to consider current (~2012, coinciding with trend end year) and more recent changes (1999 onward) in forest cover and timber conditions to see if they help explain some of the sediment changes observed in this study. → I did add these variables to the analysis and none of them were well correlated with sediment trends at undeveloped sites. I added a brief discussion of these additional results to the manuscript.

RC7: Pg. 8, ln. 25 "For TSS, undeveloped sites had the largest proportion of upward trends and some of the largest increases in TSS compared to sites in other land-use categories": again this seems to beg further explanation. Not sure if the "undeveloped sites" are forested regions mainly used for timber.

AR7: This is a possible explanation for the increasing TSS trends at undeveloped sites. These "undeveloped sites" may certainly include timber harvesting. "Undeveloped" is defined as a lack of agricultural and urban land uses. I will explore this line of inquiry further as described in above bullet. Any expanded discussion on this topic will be added to section 3.2 ("Land management changes") or section 3.4 ("Importance of location section") of the manuscript.

RC8: Pg. 8, ln 30 – 33: "Thus, the stark difference between the largely downward SSC trends and largely upward TSS trends at undeveloped sites in western US could be due to differences in the causes of changes for undeveloped sites…". OK but this is an unsatisfying explanation. The key would be to dig a bit further to help the reader understand why there are strong spatial correlations, which there appears to be from within the TSS data in Northwest US.

AR8: I included this sentence in the manuscript as a way to set up of the following sentence, "Other contributing factors could include differences in the suspended particle-size distributions being characterized by SSC and TSS and different regions having different underlying geology." I was trying to make the point that there may be other reasons that SSC and TSS trends differ apart from differences in landscape changes at these sites (such as TSS sites having increases in deforestation and SSC sites not). For example, SSC and TSS use different analytical procedures to determine suspended sediment. Also, there may be important differences in basin characteristics for SSC sites versus TSS sites. These two considerations mean that an actual change on the landscape (such as increased deforestation) may not affect SSC and TSS the same way. I will update this part of the text to clarify.

RC9: Pg 14, ln. 25-26 and Table 1: Should add forestry/logging to "Land-use and land-cover changes across entire watershed". This could explain the Northwest increase in TSS.

AR9: See above bullet. While there is not spatially and temporally consistent forestry/logging data back to 1992 there are some sources of information I can bring in to illuminate this important potential driver of change.

RC10: Pg. 17, ln 28-30: Your statement about many sites exhibiting a decrease in sediment should include a statement about the cluster of increase sediment trend in undeveloped NW US. Surely the remarkable pattern there deserves some recognition and further explanation.

AR10: Good point. I will update the conclusion accordingly.

Outlook

RC11: Pg. 17, ln. 12: This section lays out the limitations nicely. However, what is missing is a brief outlook. How can we make better sense of these results in the future? What are the priorities for this work moving forward? Is sediment pollution going to be a problem in the future? Or do the trends suggest that this problem is solved? Give the reader your take on where this research needs to go next and what the next few decades will be like based on what your learned from your analysis and the last two decades.

AR11: Agreed, adding this type of discussion would improve the manuscript by connecting the results presented here to larger issues. I will update the manuscript to include a paragraph that touches on these topics.

Minor comments

RC12: Pg. 1, ln. 23 and Pg. 17, ln. 17: You suggest that "conservation efforts" may be successful to reduce sediment runoff as lands are converted to urban and agricultural uses. These "conservation efforts" sound vague, are there any specific efforts you are speaking about. Is there any evidence, from either literature or observations, that these conservations efforts are effective? Also, Pg. 9, ln. 14: "…management actions on the landscape likely led to decreases in sediment concentration". Same comment here, this is a vague statement about management actions. Any ideas which management actions are effective in reducing suspended sediment concentrations? Are there many? Pg. 12, ln 5: "suggesting conservation efforts to reduce sediment runoff to streams may be successful". Can you be more specific here? Pg. 17, ln. 17: Again what efforts are you speaking of?

AR12: I use the terms "conservation efforts" and "management actions" in a general sense throughout the manuscript. What I mean by these terms are any actions taken in the watershed that would shift the concentration-discharge (C-Q) relationship over time. Shifts in C-Q relationships are one tool watershed managers use to evaluate progress of conservation and management efforts on water quality. For example, the Delaware River Basin Commission uses changes in the C-Q relationship as a way to detect "measurable change to existing water quality" (https://www.nj.gov/drbc/library/documents/LowerDel_EWQrpt_2016/LDel_EWQrpt_2016_entire.pdf). Also, Moatar et al. (2017) used C-Q relationships to gauge the effect of changes in point sources across streams in Europe. However, I see the point in providing some more concrete examples. To this end, I

will add some references to the paper to further elaborate on the potential conservation efforts and management actions that could lead to changes in the C-Q relationship.

Moatar et al., 2017, Elemental properties, hydrology, and biology interact to shape concentration-discharge curves for carbon, nutrients, and sediment, and major ions. Water Resources Research 53, 1270–1287, doi:10.1002/2016WR019635.

RC13: Pg. 3, ln. 18: Can you describe the mitigation measures that are being implement in the Conservation Reserve Program?

AR13: The Conservation Reserve Program (CRP) pays farmers to not farm environmentally sensitive land and instead plant environmentally beneficial plants. This can include buffer strips and wetlands. Will add text to explain.

RC14: Pg. 3, ln 26: "…to characterize changes in annual mean concentrations of suspended sediment." Are the annual means a good metric to be looking at for long term trends. Annual mean concentrations can be easily skewed by a large number of low concentration values during low flow periods (e.g., in the winter when runoff is minimal across the northern US. Wouldn't one expect to have a large amount of low suspended sediment concentrations that would skew the average. Would a clearer picture of the annual suspended sediment concentrations come from looking at annual median, 75% percentile or peaks concentrations (e.g., that come during the spring melt and/or high intensity short duration rainfall events)?

AR14: The analysis presented in this manuscript does not use a mean calculated directly from the observed samples (which would lead to "under-weighting" concentrations during high flow periods). Instead it uses modeled mean annual concentrations that are derived using a weighted regression equation that includes terms for time, season and discharge. Furthermore, the data used to the calibrate the model were screened for high flow samples so that we can be more confident that the mean annual concentrations are reflecting concentrations at high flows as well as low and moderate flows. Thus, the mean annual concentrations used in this analysis are accounting for concentrations at high flows and are not underweighting these conditions during the estimation of mean concentrations. I think adding more specific information about the methods and the relevant equations to the Supporting Information, as previously suggested by referee 1, will help to better explain this.

Additionally, the MTC and QTC approach presented in the manuscript provides a novel way to explore the influence of changing flow conditions on suspended sediment. We know that for constituents like sediment, most of the transport occurs during high flow events. Thus, changes in the flow regime, particularly at high flows, is very important to how sediment changes over time. This kind of information would be difficult, or impossible, in glean from exploring the effect of changes in mean streamflow on sediment. Thus, I argue that the MTC and QTC approach in WRTDS provides an ideal way to explore changes in mean annual concentrations because of the approach's ability to identify the effects of different types of flow changes, including changes in flow magnitudes, frequencies, and timing, on

sediment. Again, I think elaborating on the methods in the Supporting Information will make this clearer to an interested reader.

RC15: Pg. 8, ln 4-7: "Larger percent decreases tended to occur at sites with high concentrations in 1992 whereas the largest percent increases occurred at sites with low starting concentrations (Fig. SM-1)." There are only about 9 samples that fit this description on the SSC plot of Fig. SM-1. The rest which appears to be a cluster of samples (probably more than 9) are closer to a starting concentration of less than or equal to 60 mg/L. The point being that there are a large number of large decreases with low starting concentration as well. Therefore, this statement does not seem to accurately reflect what is presented in Fig. SM-1.

AR15: I agree. I think the better point to be made here is that decreases in sediment occurred at sites with low to very high concentrations in 1992, whereas increases in sediment did not occur at sites with high starting concentrations. I will update the text to clarify.

RC16: Figure 2: This is a very nice figure that should be enlarged for the Western, Central, and Eastern regions. At the continental scale it is a bit difficult to see spatial trends. Specifically, it is difficult to see the spatial distribution of triangles for TSS (especially Northwest and Eastern regions). For SCC the difficulty of seeing the spatial distribution is mainly in the Eastern regions.

AR16: I will rectify this issue by adding transparency to the symbols, eliminating the different symbol sizes, and/or enlarging all or a portion of the maps. → I decided to enlarge the maps in this figure and add outlines to the symbols.

RC17: Pg. 12, ln. 1: "…changes in the number of low-medium density dwellings … had little to no effect on the streamflow regime." I find this hard to believe, would not increase in urbanization change the streamflow regime (e.g., increase rainfall-runoff response from increased paved surfaces).

AR17: In hindsight, I agree this statement about "little to no effect on the streamflow regime" is too strong and poorly worded. I meant to make the point that the relationship between low-medium density dwellings and the QTC is much more muted compared to the MTC indicating changes in the low-medium density dwelling appear to affect overall sediment concentrations more strongly via the C-Q relationship compared to the flow regime. The QTC is describing the amount of change in sediment attributed to changes in the flow regime; there may have been considerable changes in the flow regime at many of these sites due to changes in low-medium density dwellings, but these changes did not affect sediment concentrations with the same magnitude that changes in the C-Q relationships did. I will update the text to clarify.

RC18: Pg 12, ln. 30-32: "Previous models have suggested that changes in climate will lead to increases and decreases in sediment in particular rivers or areas of the western US." This is an ambiguous statement. I suggest to delete it or elaborate a bit more with an explanation of where increases and decreases are expected.

AR18: Agreed. I will delete.

RC19: Pg. 13, ln. 24: "indicated that large decreases in streamflow relate to large decreases in sediment concentration".

AR19: I'm not entirely sure what the issue is with this quoted portion of the sentence. I will update the whole sentence to: "However, the well-defined positive relationship between mean daily streamflow and the QTC indicates that large decreases in streamflow relate to large decreases in sediment concentration (Fig. 7).

RC20: Pg 13, ln. 27-28: "…these improvements are partially offset by human activities in the waetershed." I think this partial offset you speak of is not supported by Figure 7 because the negative correlation MTC for Q slope is very weak.

AR20: Upon further review, I agree, I don't think these figures are the best to make that point (figures 4b and 4c would be better). I'm going to re-scope this paragraph so it's more about the ways that the QTC and MTC relate to different types of changes on the landscape and in streamflow. Basically, the sediment trend is largely driven by the MTC and much less influenced by the QTC. Furthermore, the MTC is more strongly related to changes on the landscape (middle-left panel of figure 7) whereas QTC is more strongly related to changes in streamflow (bottom-right panel of figure 7). Thanks for point this out. → I rescoped this paragraph and decided to keep this figure. I add more explanation to better explain this offset.

RC21: Fig. 8: Including Watershed Land-Use Change as an additional column would make this figure more insightful. I would imagine that MTC should have a stronger correlation and p-values associated with Watershed Land-Use Change.

AR21: Good suggestion. I will update the figure to include the watershed land-use change variables and add some text to discuss it. With this addition, I may or may not keep figure 7. It seems the point about what effects the MTC and what effects the QTC can be made with the expanded figure 8. → I updated the correlation heat map figure and did not delete figure 7 (now figure 6).

RC22: Pg. 14, ln. 25-32: This explanation with how to interpret Fig. 5 should be when Fig. 5 is 1st introduces (i.e., Pg. 9, ln. 26, rather than 5 pages later.

AR22: When figure 5 is first introduced (on page 9), this is in the section 3.2 "Land management changes" where I discuss the watershed land-use change variables and correlations. Page 14 is in the section 3.4 "Importance of location" and in this section I'm discussing the portion of fig 5 that has the static and long-term watershed characteristics. I think moving it up to section 3.2 would muddle the focus of that section. However, I will consider creating a separate figure for the "Static/long-term watershed characteristics" portion of the heat map – that might help clarify the different focuses of these correlations. → I did not create a separate figure. I left this explanation here because it fits better with the material in this section of the report.

RC23: Pg. 14, ln. 33: The explanation of high relative humidity leading to more vegetation and less erosion is very helpful in interpreting and understanding the results presented in Fig. 5. More explanations like these would be helpful.

AR23: Agreed. I will work in more concrete examples like this throughout the manuscript. → I added more references and examples of how changes in a land use/cover variable or hydro-climatic variable may influence water quality through. For example, I added more discussion about CRP and preferential settling of coarser material.

RC24: Pg 15, ln. 17-20: Here you indicate that QTC and MTC usually exhibit opposite trends. Can you speculate as to what this means and why this happens?

AR24: An example of this effect at a single site is given in Murphy and Sprague (2019). In that paper we showed that SSC concentrations decreased by 70% at a site on the Skunk River in Iowa, USA between 1982 and 2012. This change was attributed to a -90% MTC and 20% QTC. In Iowa the rate of soil erosion decreased in the 1980s and 1990s and this was attributed to taking erodible land out of production. These practices appear to have led to a shift in the C-Q relationship which was ultimately expressed in a -90% MTC. However, during this time there were also increases in streamflow during the spring and summer which likely lead to increased mobilization of sediment over this period and the positive 20% QTC shown at this site. Taken together, conservation practices at this site may have led to decreased sediment transport which would have been even greater if there hadn't been concurrent increases in streamflow. I can see how giving some more examples and elaborating on these "opposing effects" would greatly help the reader. Thanks for the suggestion. → I added this example the text.

Murphy and Sprague, 2019, Water-quality trends in US rivers: Exploring effects from streamflow trends and changes in watershed management. Science of the Total Environment 656, 645-658. https://doi.org/10.1016/j.scitotenv.2018.11.255

RC25: Pg. 15, ln 25-27: Here you mention that 1 SSC and 10TSS trends had a large change in sediment and MTC near zero. Is there a reason for this? Is there a spatial pattern for these sites? What is special about these sites?

AR25: I pointed out these 11 sites because I wanted to emphasize how uncommon it was for changes in sediment to be totally driven by changes in the flow regime alone (no concurrent changes in the C-Q relationship). However, I see now that I could elaborate a bit about these sites. I will explore these sites in more detail to see if there are any spatial patterns or particular land use changes associated with them. → Upon further consideration, I decided not to include additional exploration or discussion on this set of sites. Updating the manuscript to address the comments from both referees lengthened to the text and I did not feel the additional text for these 11 sites would be worth adding at this point.

RC26: Pg. 17, ln. 19: You state here that land management was the primary contributor of changes in sediment. Can you give the average percentage? You also state that streamflow regime had a mild-to-moderate influence on sediment. Can you give the average percentage here? The purpose of this comment is to move away from a qualitative statement to a quantitative one.

AR26: Good point. I will update this portion of the text with the appropriate numbers.

RC27: Pg. 17, ln 23-25: The proximal zone results is not discussed in very much detail in the manuscript and adds little insight. I would suggest removing it from the main text and figures. Move it to the supporting information.

AR27: Agreed. That analysis was underwhelming and does not add much to the overall interpretation. I will move to Supporting Information which will free up more space in the manuscript for some additional discussion.

RC28: Fig. 5: Fracking wells is negatively correlated for SSC in undeveloped lands. Can you explain why this may be the case? I can imagine that fracking activity would require large quantities of groundwater extraction and that this could decrease local stream baseflows, leading to higher TSS and SSC values. Instead the opposite is true, can you explain?

AR28: Thank you for this comment. I went back and reviewed the bivariate plots for each of the correlations reported in Fig. 5. For SSC in undeveloped lands, there are 4 sites with large changes in fracking and one of which had a much higher % change in fracking than the others. This single site is leveraging the whole relationship. Also, it appears a similar thing is happening with changes in "Mining and related activities" (2 sites with large changes are dictating the relationship). Thus, I'm going to drop these two variables from the analysis since they are skewing the correlations and do not provide much insight. Again, thank you for noting this.

RC29: Fig. 7: In the 'Low-med density dwellings' column, there appears to be a number of undeveloped and mixed land-use points located along a vertical line on the zero change in low-med density dwellings. Is there an explanation for this pattern? Also, have you considered non-linear regression? Did any of the relationships exhibit nonlinear dependencies?

AR29: The cluster of undeveloped and mixed land-use sites along the vertical axis are sites that did not see any change in the percent of watershed with low-medium density dwellings but did have a change in sediment concentration. For these sites, something other than a change in low-medium density dwellings (since there was no change) effected sediment concentration. I will update the text to make this clearer.

I did not consider non-linear regression; however, I am using Kendall's tau for the correlation analysis which is a rank-based, non-parametric method for assessing bivariate relationships. I chose Kendall's tau over Pearson's r because most of the data do not follow a normal distribution. Using Kendall's tau also does not require the assumption of linearity, just that the relationship be monotonic.

Response to Referee #2

RC: This manuscript presents an extensive data set of suspended sediment and TSS trends at 137 stream sites across the contiguous US and explores potential drivers of these changes. Overall, I think the manuscript is well written and will become a worthwhile contribution to the hydrological community. The proposed method also has the potential of being applied elsewhere. I do have some comments for the author, which I hope can help improve the manuscript.

AR: Thank you for the supportive and constructive comments on my manuscript. I've provided author respondes (AR) to the referee comments (RC) below.

RC1. On the flow-normalization trend method: It would be helpful to provide an example to guide the readers through the calculations of MTC and QTC and how the two approaches differ from each other. This essential information could be shown as Figure 1.

AR1: Referee 1 also requested additional information and explanation of the MTC and QTC methodology and suggested adding this information to the Supporting Information. Showing how the methods are applied at a specific site is another interesting suggestion. I will spend some time thinking about the best way to incorporate additional, clarifying information about the methods – either in the Supporting Information or in the manuscript with a figure. ← I added a section in the Supplemental Material that gives a more elaborate explanation of the methods and explicitly points the reader to where they can find site-specific examples of how the MTC and QTC calculations are completed.

RC2. On the use of sediment concentration: Why is not sediment flux used instead? Given that both concentration and flux are assessed in the flow-normalization, why did the author choose to focus on concentration in this work?

AR2: I went back and forth about this choice prior to beginning the analysis. Ultimately, I decided to go with sediment concentration because my primary goal of this analysis was to explore potential drivers of change. Since sediment loads are very closely related to streamflow, I thought I would be better able to identify the influence of other changes, such as land use and climate, if I used concentration (better able to get the "signal" out of the "noise" using concentration as opposed to load). I decided to only go with concentration, as opposed to concentration and loads, to keep the manuscript digestible. I suspect

many of the conclusions will be similar between concentration and load because streamflow is typically positively related to both concentration and load (so increases in Q are likely to lead to increases in concentrations and loads).

RC3. Abstract: Suggest adding an opening sentence to place the work into a broader context. Also, suggesting adding 1-2 sentences to highlight the implications and relevance of the major findings.

AR3: Ok will do. → I added a sentence that provides broader context, but I decided not to lengthen the abstract by adding additional sentences. As written, the abstract highlights the major findings and connects them with large implications. For example statement like, "Correlations between sediment trends and concurrent changes in land use/cover, hydrology and climate were often stronger at sites draining watersheds with more homogenous, human-related land uses…", and "decreases in sediment … conservation efforts and best management practices used to reduce sediment runoff to streams may be successful, up to a point, even as lands are converted to urban and agricultural uses.", are already included in the abstract.

RC4. P2L22: List some examples under the category deterministic approaches and empirical approaches.

AR4: Good point, I will update. → Upon further reflection, this part of the paragraph is reflecting on recent empirical approaches for identifying potential drivers of change for water quality. I updated the sentence to clarify that.

RC5. P3L1: Be more specific on "the latter two contributions" and support this argument with literature.

AR5: I will enhance this paragraph to better support these ideas.

RC6. P3L4-L23: I appreciate these thoughtful statements on the relative effects of streamflow and landscape management. However, how about efforts/practices that might affect both the streamflow regimes and landscape functioning?

AR6: I agree that there are plenty of efforts/practices that affect both streamflow regimes and landscape functioning. I plan to dig into that more throughout the entire manuscript but will add some discussion on that here in the introduction as well. → I expanded figure Fig. 7 (originally Fig. 8) to include correlations between the land use/cover variables and MTC or QTC. I also added text in Section 3.3 Hydro-climatic changes that further discusses this topic.

RC7. P3L25: "suspended sediment and total suspended solid"

AR7: Will add.

RC8. P6L8: What is the window for loess smoothing?

AR8: Loess smoothing was applied in R using the loess() function with the span argument set to 0.75. Meaning 75% of the points are used in each window and these points have tricubic weight. Will update text to clarify.

RC9. P8L30: Could you support this last sentence by showing the distribution of trends among different regions for just the undeveloped sites?

AR9. Referee 1 also noted this sentence as being vague. I plan to drop this sentence ("Thus, the stark difference between the largely downward SSC…."). Most of the undeveloped sites are in the Western US. Site counts for the other geographic regions are too small to gain much insight. For SSC sites, there are 12, 1, and 2 sites in the Western, Central, and US regions. For TSS sites, there are 18, 5, and 6 sites, respectively.

RC10. P10L3-L16: I appreciate these discussions by the author. However, this is not well supported by the scientific literature. Could you provide some relevant references?

AR10: I respectfully disagree. It is well supported that TSS determinations are more uncertain that SSC determinations, and typically biased low. TSS determinations tend to result in a "sediment deficient" subsample based on the techniques used to retrieve a subsample from the original sample for analysis. These issues become more severe with increases in the proportion of sand-sized sediment in a sample. See method comparison by Gray et al (2000). While I discuss Gray et al (2000) in other places in the manuscript, I see that I did not include it in this section. I will rectify that issue.

Additionally, many studies have shown the preferential settling of coarser material as streamflow slows. With respect to conservation practices, White et al. (2007) showed that forested filter strips are efficient at removing coarse-textured sediment (> 20 um in diameter) but that small particles (<2 um, generally clay and smaller) are not affected. Lee et al. (2000) found that trapping efficiencies varied depending on the vegetation type used in vegetative buffers but were highest for coarse sediment. Meyer et al (1995) found that grass hedges trapped nearly all sand-sized sediment but allowed silt and clay-sized sediment through. Bimbino et al. (2008) found decreases in sediment size over a reach that had 3 check dams. I do agree this section of the manuscript lacks supporting references, so thank you for that comment. I will update the manuscript with appropriate references, such as the ones described above.

Gray, J.R., Glysson, G.D., Turcios, L.M., and Schwarz, G.E.: Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data. U.S. Geological Survey Water-Resources Investigations Report 00-4191, 2000.

White et al., 2007, Sediment retention by forested filter strips in the Piedmont of Georgia. Journal of Soil and Water Conservation 62, no. 6., 453-463.

Lee et al., 2000, Multispecies Riparian Buffers Trap Sediment and Nutrients during Rainfall Simulations. Journal of Environmental Quality 29, n. 4., 1200-1205.

Meyer et al., 1995, Sediment-trapping effectiveness of stiff-grass hedges. Transactions of the American Society of Agricultural and Biological Engineers 38(3): 809-815.

Bombino et al., 2008, Sediment size variation in torrents with check dams: Effects on riparian vegetation. Ecological Engineering 32, 166-177.

RC11. P11L14: Any reference on these stated effects of CRP?

AR11: Often process-based watershed models (such as SWAT) are used to assess the effectiveness of conservation practices on water quality, for example see the US Department of Agriculture's Conservation Effects Assessment Project (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd889806.pdf). However, identifying these effects empirically has proven challenging. To my knowledge, no one has assessed the influence of CRP on sediment transport nationally (some studies have been done for nutrients, see Sprague and Gronberg (2012)). Studies completed at individual basins give a mixed story. Davie and Lant (1994) found CRP enrollment influenced sediment erosion rates but not sediment loads downstream. They also suggest that the location of CRP near the stream might be important for effecting downstream sediment load. Support for this idea is shown in figure 6b. Lizotte et al. (2012) found decreases in sediment in an oxbow lake related to the implementation of best management practices and CRP enrollment in the surrounding drainages. Cullum et al. (2010) found the conversion of cropped land into forested CRP land in the drainage surrounding an oxbow lake reduced the sediment load entering the lake by an order of magnitude. I will enhance this section of the report by elaborating on the documented effects of CRP in individual watersheds and discuss the difficulty of gauging these effects on a national scale.

Davie, D.K., and Lant, C.L., 1994, The effect of CRP enrollment on sediment loads in two southern Illinois streams. Journal of Soil and Water Conservation 49(4), 407-412.

Lizotte, et al., 2012, Water quality monitoring of an agricultural watershed lake: the effectiveness of agricultural best management practices. Transactions on Ecology and the Environment 160, doi:10.2495/DN120251.

Cullum, et al., 2010, Effects of Conservation Reserve Program on Runoff and Lake Water Quality in an Oxbow Lake Watershed. Journal of International Environmental Application and Science 5, (3): 318-328.

RC12. P13L14: One very relevant example on the effects of dams on sediment trend is the Conowingo Dam on Susquehanna River. There are also documented effects of many small mill dams in the mid-Atlantic region.

AR12: Agreed. It was surprising the effects of dams were not more pronounced in this study. The manuscript provides several reasons why this may be the case.

RC13. Figure 1: I don't think this figure is necessary. You may move it to SM.

AR13: Agreed. I will be moving the analysis pertaining to the riparian land-use change to the Supporting Information.

RC14. Table 3: I found the table with such lengthy descriptions difficult to follow. Could you convert it to a figure or shorten the descriptions?

AR14: I respectfully decline this suggestion. I am unsure how this table could be converted to a figure and the descriptions are about as concise as I can make them. The bolded portion of the table provide the information in a succinct format; the descriptions are provided so that a reader can gain a better understanding of how to interpret the magnitude and direction of MTC and QTC estimates.

RC15. Figure 2: Consider using smaller symbol to make the Eastern stations more distinct. I appreciate that the author is using the font size to represent different magnitudes, but that might be less important. Alternatively, and perhaps more conveniently, enlarge the size of the figure to be full-page so the stations can be more distinguishable.

AR15: Referee 1 also had issue with Figure 2 and the clustering of sites. I will rectify this issue by adding transparency to the symbols, eliminating the different symbol sizes, or enlarging all or a portion of the maps. ← I ended up enlarging the maps in the figure and outlining the symbols. I believe these two changes make these maps easier to read now.

RC16. Figure 3: There are outliers for many of the boxplots. What are those stations and why they have such large trends? This deserves attention from the readers and more discussion by the author.

AR16: My goal for this paper is to present a national perspective on changes in sediment concentration since 1992 across the US. Thus, I chose not to explore and elaborate on these sites with outlier changes in sediment since these likely present unique situations.

RC17. Figure 5: I think this is such an important figure in the manuscript and it deserves to be made larger (say full-page) to be clearer. How about transposing this figure?

AR17: My plan is to move the riparian land-use change analysis and results to the Supporting Information. Doing this will remove the riparian land-use change correlations from Fig 5 and will allow more space for what remains. I will also explore transposing the figure. ← I decided not to transpose this figure. Instead I moved the proximal zone correlations to the Supplemental Materials. This allows for more space for the remaining variables.

~~Declining~~ Changing suspended sediment in United States rivers and streams: Linking sediment trends to changes in land use/cover, hydrology and climate

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Abstract. Sediment is one of the leading pollutants in rivers and streams across the United States (US) and the world. Between 1992 and 2012, concentrations of annual mean suspended sediment decreased at over half ~~(58%)~~ of the 137 stream sites assessed across the contiguous ~~United States~~ (US). Increases occurred at less than ~~17~~25% of the sites and the direction of change was uncertain at the remaining 25%. Sediment trends were characterized using the Weighted Regressions on Time, Discharge, and Season model, and decreases in sediment ranged from -95% to -8.5% of the 1992 concentration. To explore potential drivers of these changes, the sediment trends were (1) parsed into two broad contributors of change, changes in land management versus changes in the streamflow regime, and (2) grouped by land use of the watershed and correlated to concurrent changes in land use/cover, hydrology and climate variables and static/long-term watershed characteristics. At 83% of the sites, changes in land management (captured by changes in the concentration-streamflow relationship over time) contributed more to the change in the sediment trend than changes in the streamflow regime alone (i.e. any systematic change in the magnitude, frequency or timing of flows). However, at >~~60~~50% of the sites, changes in the streamflow regime contributed at least a 5% change in sediment and at ~~10~~ 11 sites changes in the streamflow regime contributed over half the change in sediment, indicating that at many sites changes in streamflow were not the main driver of changes in sediment but was often an important supporting factor. Correlations between sediment trends and concurrent changes in land use/cover, hydrology and climate were often stronger at sites draining watersheds with more homogenous, human-related land uses (i.e. agricultural and urban lands) compared to mixed-use or undeveloped lands. At many sites, decreases in sediment occurred despite small to moderate increases in the amount of urban or agricultural land in the watershed, suggest~~ing~~ conservation efforts and best management practices used to reduce sediment runoff to streams may be successful, up to a point, ~~even~~ as lands are converted to urban and agricultural uses.

1 Introduction

Across the United States (US) and the world, sediment is one of the leading pollutants in rivers and streams (USEPA, 2008-2016; Walling, 2009), degrading aquatic habitats and affecting water usability (Brown and Froemke, 2012; Wohl, 2015). River monitoring programs of sediment are typically implemented to collect data to characterize status and temporal changes
5   in the delivery of suspended material, often with an explicit goal of capturing improvements. An implicit goal of many of these programs is better understanding of why sediment delivery has or has not varied over time (Irvine et al., 2015). To optimize the ability to characterize and detect temporal changes, many monitoring programs focus on implementing the best sampling design. A missing piece is often the observation and characterization of potential ~~causes~~ drivers of these changes in sediment (Irvine et al., 2015), such as shifts in land use or land cover (land use/cover), changes in management of the
10 landscape or stream, or climatic variability.

There are multiple approaches for linking changes in sediment at stream sites with changes in land use/cover, hydrology and climate. These approaches include using qualitative statements with or without data (e.g. Gao et al., 2013; Kreiling and Houser, 2016; Li et al., 2016), using process-based watershed and landscape models (e.g. Ficklin et a., 2013; Lacher et al.,
15 2019) and teasing apart water-quality and streamflow records to identify and estimate the amount of change due to human actions, ~~or~~ climate ~~and~~ or hydrology (e.g. ~~Wu et al., 2012;~~ Gao et al., 2013; Li et al., 2016; Murphy and Sprague, 2019; Choquette et al., 2019; Rossi et al., 2009). Many of these approaches are hindered by the lack of available data that characterize potential drivers of change. Such data are often not available or not available across many sites. Some studies have used geospatial data to generate estimates of various land-use and land-disturbance metrics and have been successful at
20 linking these to spatial variations in static water-quality conditions (e.g. Mehaffey et al., 2005; Carey et al., 2011). ~~This geospatial approach compares~~Using static land-use conditions (either current or long-term average conditions) ~~to~~ and recent water-quality conditions ~~and~~ provides information about ~~the~~ spatial variability ~~of water quality across many sites; however, this approach~~but does not explicitly explore how temporal changes in land use/cover or other human activities affect water quality. Other studies have begun to explore the effect of temporal changes on water quality by explicitly considering land-
25 use/cover, land-management and hydrologic changes over time using empirical approaches such as ~~hybrid deterministic-empirical approaches (Chanat and Yang, 2018)~~, structural equation models (Ryberg, 2017; Ryberg et al., 2018), hybrid deterministic-empirical approaches (Chanat and Yang, 2018) or focusing on a couple of specific potential causes in a limited geographic area (Schottler et al., 2014; Panthi et al., 2017). Historically, field-based assessments in specific areas have been successful ~~in~~ at identifying and supporting causal understanding of changes in river sediment (e.g. Wolman and Schick,
30 1967; Trimble and Lund, 1982; Gellis et al., 1991).

~~Due to the sensitivity of sediment to streamflow conditions~~At many sites, concentrations (or loads) of annual mean sediment covary with annual streamflow conditions ~~at many sites~~. Much of this year-to-year variability in streamflow is dependent on

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weather, though at some locations there may also be a longer-term systematic change in streamflow that also influences sediment. Thus, for a given year, annual mean concentrations of sediment are a function of the streamflow conditions for that year, changes that occurred in the ~~basin~~ watershed (i.e. land-management activities, surface or channel disturbance, etc.), and, at some locations, a systematic change in some portion of the streamflow regime (Murphy and Sprague, 2019; Choquette et al., 2019). When trying to understand potential drivers of long-term changes in sediment, it is the ~~latter two contributions~~influence of land management changes ~~in basin~~ and systematic changes in streamflow that are of most interest.

All rivers have a characteristic streamflow regime that captures the typical pattern of fluctuations in the magnitude, timing and frequency of streamflow across a given year. Individual years may be wetter or drier due to variations in weather but under a stationary climate and limited human influences, these fluctuations are within expected ranges for a given streamflow regime. And as mentioned above, these year-to-year fluctuations are of less interest when trying to understand multi-year and multi-decade changes in water quality. However, systematic changes in the streamflow regime over time caused by ~~Under stationary climate, a streamflow regime is also often stationary; hHowever, nN~~natural and anthropogenic influences, such as increases in precipitation or a change in dam operations, ~~can cause~~are important when trying to understand long-term water-quality changes ~~changes in the streamflow regime over time~~. ~~These cC~~hanges in the streamflow regime can occur in many forms, such as increases in mean streamflow, decreases in high streamflow events or a shift in high streamflow from spring to winter. Changes in the streamflow regime may ultimately lead to changes in sediment concentrations in a stream because of shifts in transport processes or changes in which channel or near-channel sediment sources are eroded. This can include geomorphological changes like increased headcutting and channel bank sloughing, as well as channel bottom scouring and resuspension.

The effect of streamflow-related changes on sediment can be compared to changes in sediment resulting from management and disturbance on the landscape ~~across the watershed~~. Changes in land~~scape~~ management (including surface disturbance and other human actions in the watershed) may enhance or ~~aim~~try to minimize the sediment available for transport to a stream via overland runoff. For example, changes in the amount of land used for grazing or crops, changes in tillage practices, increased construction in suburban or exurban areas, increases in mining or harvesting of timber can all lead to enhanced erosion. However, other management actions, such as ~~widespread implementation of~~ agricultural conservation practices,~~or~~ urban best-management practices (BMPs), ~~enroll~~enrolment~~ing of~~ of agricultural land in the Conservation Reserve Program (CRP) and channel restoration efforts, ~~are aimed at~~attempt to ~~reducing~~reduce erosion or trap~~ping~~ eroded sediment. ~~The~~CRP mitigation measures ~~of CRP~~ include paying farmers to remove environmentally sensitive land from production and plant erosion-controlling and ecologically beneficial plants instead. Attributing sediment trends to these broad categories of change (i.e. land~~scape~~ management versus the streamflow regime) provides ~~promise~~a means for better understanding the

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relative influence of largely controllable human influences on sediment in streams, resulting from changes in land management and surface disturbance, compared to the influence of less controllable changes in the streamflow regime.

In this paper, an extensive dataset of temporal changes in land use/cover, hydrology and climate ~~(Falcone, 2017; Falcone et al., 2019; Farmer et al., 2017)~~ is used in conjunction with two decades of sediment and streamflow data ~~(De Cicco et al., 2017; Oelsner et al., 2017)~~ to characterize changes in annual mean concentrations of suspended sediment and total suspended solids (hereafter referred to collectively as sediment) and explore potential drivers of these changes at 137 stream sites across the contiguous US. The objectives are to (1) summarize and describe sediment trends between 1992 and 2012, (2) explore contributions to sediment trends from changes in land~~scape~~ management versus changes in the streamflow regime and (3) link specific land -use/cover changes, ~~and~~ hydro-climatic changes ~~(across the watershed and for a near-site, near-stream "proximal" zone)~~ and static and long-term watershed characteristics to sediment trends. This paper builds off the insights presented in Murphy and Sprague (2019) by explicitly exploring contributions from changes in land~~scape~~ management versus changes in the streamflow regime for sediment, regionally and by land use. It also goes beyond the analysis presented in Murphy and Sprague (2019) by exploring changes in overall sediment across the US, how these changes in sediment vary regionally and with land ~~use, and~~use and links these sediment changes ~~in sediment~~ to observed changes in land use/cover, streamflow and climate. The overarching goals of this effort are to better understand how sediment concentration has changed over time across the US and to provide insight into the potential drivers of these trends.

2.0 Methods

2.1 Description of water-quality data and trend results

This study relied on the water-quality data and trend analyses described in Oelsner et al. (2017) ~~—a —~~ a comprehensive water-quality and ecology trend assessment of US rivers ~~for multiple water-quality and ecologic metrics~~, spanning four trend periods beginning as early as 1972. With nearly 12,000 reported trend results for approximately 1,500 sites, the focus of their publication was to document data acquisition, harmonization and screening processes and the trend analysis methods. The trend results and data were published in De Cicco et al. (2017) and Murphy et al. (2018). The data originated from 74 Federal, state and local governments and organizations that collect and process stream water-quality samples across the contiguous US. Each site was associated with a streamflow gage. For this paper, the 1992 to 2012 sediment trends (annual estimates and changes) were extracted from Murphy et al. (2018) and sites with drainage areas < 300,000 square kilometers (sq km) were retained; 7 sites that had very large drainages ranging from 410,000 sq km to 1,080,000 sq km were excluded. An additional site, on the Atchafalaya River in Louisiana (site number 07381495), was also excluded because a large proportion of the water at this site is diverted from an adjacent ~~drainage basin~~watershed. The extracted sediment trends included results for suspended-sediment concentration (SSC) and total suspended solids concentration (TSS), at 99 sites and

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41 sites, respectively. A few sites (n = 3) had data and trends for both parameters, resulting in 137 unique sites overall. All analyses were completed using the R statistical software program (R Core Team, 2018).

SSC and TSS characterize suspended material in the river column, but these estimates are not directly comparable and must
5   be interpreted somewhat differently. ASTM Standard Test Method D 3977-97 was used for SSC determinations (American Society for Testing and Materials, 2000) and Method 2540 D, with some variations (Gray et al., 2000), was used for TSS determinations (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995). The difference in SSC and TSS determinations is largely due to differences in the water-sample preparation procedures, resulting in different suspended particle-size distributions for the same water sample. The
10   comparability of these sediment parameters is described in Gray et al. (2000) and briefly summarized here. SSC is determined by measuring the dry weight of all sediment from a water sample of a known volume. Several techniques are used to determine TSS and most techniques similarly measure the dry weight of all sediment from a water sample of a known volume; however, this technique as defined by the TSS protocol (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995) weighs the sediment in only a 100-milliter sub-
15   sample from the original water sample. Due to the physical properties of sediment and water, taking an aliquot of the original water sample tends to leave larger particle sizes (often sands) in the original sample. Thus, TSS generally characterizes only finer suspended particle sizes, whereas SSC characterizes the entire suspended particle-size distribution of the original sample and presumably the river. The downward bias of TSS compared to SSC, especially at sites with larger proportions of sand-size sediment, is an important consideration when interpreting changes in TSS or comparing TSS to SSC. Both
20   parameters are reported here because SSC determinations are more accurate, reliable and presumably characterize the entire suspended particle-size distribution of the sampled stream, whereas TSS determinations are much more common across the US.

Oelsner et al. (2017) and Murphy et al. (2018) provide a complete description of the modelling specifications used to
25   generate trends presented in this study. Briefly, the Weighted Regressions on Time, Discharge and Season model (WRTDS; original: Hirsch et al., 2010; updates: Hirsch et al., 2018a; Choquette et al., 2019) was used to calculate trends between 1992 and 2012. For each site, WRTDS estimates daily mean concentrations using weighted regression. These estimated daily concentrations are flow normalized (FN) to remove the influence of year-to-year variability from streamflow, which is mostly weather-driven, and the non-FN and FN daily estimates are separately aggregated to non-FN and FN annual mean
30   concentrations. Flow normalization is an approach for identifying the "signal" of long-term systematic water-quality changes due to human actions on the landscape from the "noise" of high year-to-year variability. a physically based smoothing technique that uses the observed streamflow values to This process provides an estimates of concentration that excludes effects from random of year-to-year fluctuations in streamflow, due largely to variability in weather, but retains the effects

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from both seasonal streamflow variability and long-term, systematic streamflow trends, both of which may influence long-term systematic changes in water quality (Choquette et al., 2019). Trends are reported as the time series of FN annual values and as the change (in both milligrams per liter (mg/L) and percent change relative to initial concentrations) between the 1992 and 2012 FN sediment concentration. Thus, the 1992-2012 trend was calculated as (FN2012 – FN1992)/FN1992*100. See

5 Hirsch et al. (2010), Hirsch et al. (2018a) and Choquette et al. (2019) for a complete description of the trend methods, including the weighted regression approach and the flow-normalization process. These analyses were completed using the statistical software R (R Core Team, 2018) and the EGRET version 3.0 R package (Hirsch et al., 2018a). Furthermore, to gauge the uncertainty of the trends, likelihood estimates of the trend direction for each site and parameter were extracted from Murphy et al. (2018). These estimates are described in Oelsner et al. (2017) and Murphy et al. (2018) and use a A

10 block-bootstrapping approach was used and is presented in Hirsch et al. (2015) and further refined in Hirsch et al. (2018b). The modelling specifications for deriving these estimates are described in Oelsner et al. (2017) and Murphy et al. (2018). Upward or downward trends were considered "likely" if the likelihood was > 0.85, "somewhat likely" if the likelihood was from 0.85 to 0.70, and "as likely as not" to be upward or downward if the likelihood was < 0.70. See the Supplementary Material for more method detailsinformation. The efficacy of using WRTDS for estimating trends in sediment concentration

15 and flux has been explored and discussed in Moyer et al. (2012), Chanat et al. (2016) and Lee et al. (2016).

2.2 Description of watershed data and changes

For each site, 52 344 estimates variables of land use/cover change, hydro-climatic change and static/long-term watershed characteristics (Table 1) were generated or compiled using data from Falcone (2017) and Farmer et al. (2017). Falcone

20 (2017) includes time-series variables characterizing land use/cover and climate for each watershed. When possible, land use/cover variables were also generated and for a near-site, near-stream zone, which was were computed as 25% of the watershed area nearest the site and stream (Fig. SM-1) and hereafter referred to as the proximal zone. For this study, the percent change, relative to the starting condition, of each variable was calculated using the years closest to 1992 and 2012, i.e. (variable2012 – variable1992)/variable1992*100. The spatial resolution and frequency of data collection varied by

25 variable. Data collected at the annual time scale were smoothed using locally weighted regression (loess) prior to calculating percent change to characterize the systematic change in these variables over time. Loess smoothing was completed using the loess function in R with the span argument set to 0.75, meaning 75% of the years were used in each window. The static/long-term watershed characteristics were also extracted from Falcone (2017). Three variables characterizing trends in streamflow were retrieved from Farmer et al. (2017) for each site. See Table 1 for a list of all variables and brief descriptions; also, see

30 the Supplemental Material for additional proximal zone variables. See Falcone (2017) and Farmer et al. (2017) for specific information about data processing and original source information for these data.

Each site was ~~also~~ assigned to 1 of 4 categories describing the predominant land use in the corresponding watershed (urban, agricultural, undeveloped or mixed-use), based on the categorization scheme provided in Falcone (2015). See Supplemental Material for the explicit land-use categorization scheme used in this study. Across all 137 sites with either SSC or TSS data, 7 sites switched land-use categories between 1992 and 2012. All seven watersheds became more urban, shifting categories from mixed-use, agricultural or undeveloped to urban or mixed-use. For consistency, and because the specific reason(s) that caused a site to switch land-use categories presumably corresponds to the land-use category at the end of the record (e.g. increased urbanization caused an agricultural watershed to become an urban watershed), the 2012 land-use categorization was used to group sites.

2.3 Methods for exploring potential drivers of change

Since the potential drivers of systematic, multi-decadal changes in sediment in US rivers and streams are varied, one useful approach is to conceptualize changes in sediment as a function of changes in the streamflow regime ~~versus~~ and changes on the landscape (Choquette et al., 2019; Murphy and Sprague, 2019). Thus, each sediment trend was parsed into two components of change: the amount of change due to changes in the streamflow regime, i.e. the streamflow trend component (QTC), ~~versus~~ and the amount of change in sediment due to changes in land~~scape~~ management, i.e. the management trend component (MTC). These estimates, which can be found in Murphy et al. (2018), were compared across watershed land uses, geographic ~~location~~ regions and sediment trend magnitudes. Choquette et al. (2019), Hirsch et al. (2018a) and Murphy and Sprague (2019) provide details about the method used to parse water-quality trends into QTC and MTC contributions.

Briefly, the sediment trend can be described as an additive function of the MTC and QTC, the absolute and relative contributions of which provide insight into broad drivers of change (Choquette et al., 2019; Murphy et al., 2019). MTC is estimated as the sediment trend assuming a stationary streamflow regime. As such, MTC describes the potential amount of change in sediment concentrations over time due to factors other than long-term systematic changes in the streamflow regime. This estimate isolates the amount of change in sediment due to changes in the concentration-streamflow (C-Q) relationship (Choquette et al., 2019; Murphy and Sprague, 2019), also often referred to as a sediment rating curve. Changes in C-Q relationships are often used to identify and understand human influences on water quality (e.g. Moatar et al., 2017; Murphy et al., 2014; Basu et al., 2010; Bieroza et al., 2018). Choquette et al. (2019) and Hirsch et al. (2018a) refer to the MTC as the CQTC (concentration-streamflow trend component) but this analysis uses the more conceptual terminology presented by Murphy and Sprague (2019). Analytically, the MTC is estimated using WRTDS ~~and~~ with a stationary streamflow regime ~~is~~ specified during the flow-normalization procedure. ~~When t~~The MTC is subtracted from the sediment trend~~, this gives~~ to give the QTC. QTC describes the potential amount of change in sediment concentrations over time due specifically to long-term, sustained changes in any aspect of the streamflow regime. These could be changes in the

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magnitude, timing or frequency of streamflow that ultimately effect sediment. Taken together, the sediment trend is the sum of the MTC and QTC. See the Supplemental Material for more information. Also, ~~S~~see Choquette et al. (2019), Hirsch et al. (2018a) and Murphy and Sprague (2019), for a complete description of these methods including example applications at individual sites and extended discussion on interpreting these types of estimates. Additionally, while Murphy and Sprague (2019) present estimates of MTC and QTC for sediment at some of the same sites in this paper (though for a longer trend period), the results presented here greatly expand that initial investigation by comparing these estimates regionally, by land use, to the magnitude of the overall change in sediment, and to observed land use/cover changes, ~~h~~hydro-climatic changes and static/long-term watershed characteristics.

Finally, to link sediment trends to specific changes in land use/cover, hydrology and climate, plus static/long-term watershed characteristics that might influence how responsive a site is to change, a correlation analysis was completed. The Kendall's Tau correlation coefficient (Kendall, 1938) was computed between the sediment trend, in percent change, and each of the ~~34~~ ~~22~~24 potential causal variables (~~13~~15 land use/cover ~~of the watershed~~ and ~~12 of the proximal area,~~ 9 hydro-climatic changes, Table 1). For correlations with the ~~18~~20 static/long-term watershed characteristics (Table 1), the sediment trend in absolute percent change was used. These potential causal variables were selected because they ~~characterize, or~~characterize or serve as a proxy for~~partially characterize,~~ some possible driver~~s~~ of ~~sediment concentration~~ change and the available data were temporally and spatially consistent. The static/long-term watershed characteristics describe various physical features of the watershed that could influence the sensitivity of sediment at a site to changes in the watershed. Kendall's Tau is a non-parametric alternative to Pearson's correlation and was used because of the non-normal distributions of the variables. ~~All analyses were completed using the R statistical software program (R Core Team, 2018).~~

3.0 Results and Discussion

3.1 Sediment concentration trends

~~Since~~ In the two decades following 1992~~1992~~, sediment concentrations largely decreased at the 137 rivers and stream sites across the contiguous US. ~~These d~~Downward trends were more common and had larger magnitudes for SSC trends compared to TSS trends (Table 2~~)~~). and ~~. For both SSC and TSS, Larger percent decreases tended to occur at sites with high concentrations in 1992 whereas the largest percent increases occurred at sites with low starting concentrations~~sites with the highest starting concentrations tended to have decreases in sediment regardless of the sediment parameter ~~-~~(Fig. SM-3~~1~~). Starting concentrations were typically lower for TSS compared to SSC (Table 2) reflecting a combination of differences in analytical procedures and different sets of sites.

Decreasing Ssediment trends were widespread varied geographically across the US with increasing concentrations occurring at localized clusters of sites (Fig. 1). Between 1992 and 2012, iIncreases in SSC occurred exclusively only at sites in the eastern US (Fig. 2Fig. 1) where the median percent change was 5%. SSC sites in the western and central US had large decreases in sediment (, and median percent changes in SSC were of -45%; and -23% and 5% for sites in the western, central and eastern US, respectively (Fig. 3Fig. 2a)). Increases in TSS occurred at sites across all geographic regions (Fig. 1) with a pronounced cluster of sites with a median increase of 18% in the western US (Fig. 2a). trends mostly decreased at sites in the central US, with a median percent change of about -23% (Fig. 3Fig. 2a). However, TSS trends had the opposite pattern of change for sites in the western and eastern US compared to SSC trends; median percent changes for TSS trends were 18% and -17%, respectively (Fig. 3Fig. 2a). The location of sites within each geographic region differs between parameters. For example, in the western US, sites with TSS trends were clustered in the northwestern US while sites with SSC trends were spread across the western US more generally (Fig. 2Fig. 1). Similarly, in the eastern US, sites with TSS data were spread across the region while there were almost no sites with SSC trends in the southeastern US (Fig. 2Fig. 1). These differences in the geographic distribution of SSC compared to theand TSS sites, are an important consideration for understanding potential drivers of sediment trends. at least partially, account for some of the differences in trend direction and magnitude between sediment parameters in the same geographic region.

Like other studies, categorization of sites by the land- use of their contributing categorization of the watershed yielded different patterns of sediment trends (Oelsner and Stets, 2019; Lacher et al., 2019). At aAgricultural, urban and mixed-use siteswatersheds tended to have larger proportions of sites with decreasing sediment (Fig. 2b)., there was an overall decrease between 1992 and 2012 for both SSC and TSS. At urban, undeveloped and mixed-use sites, the patterns of trends differed between sediment parameters. For SSC, uUndeveloped sites had the largeest decreases in SSC but increases in TSS, with median changes of -41% and with a median percent change of -4115%, respectively (Fig. 2b). Urban sites and mixed-use sites had a larger proportion of upward SSC trends with median percent changes of 3% and -6%, respectively (Fig. 3Fig. 2b). For TSS, undeveloped sites had the largest proportion of upward trends and some of the largest increases in TSS compared to sites in other land-use categories. Urban sites and mixed-use sites typically had decreases in TSS, with median percent changes of -13% and -21%, respectively (Fig. 3Fig. 2b). The proportion of sites with various watershed land uses is relatively similar across geographic regions for both sediment parameters. For example, undeveloped sites largely occur in the western US and agricultural sites largely occur in the central US for both sediment parameters (Fig. SM-2). Thus, tThis marked e stark difference in trend direction between SSC and TSS at undeveloped sites between the largely downward SSC trends and largely upward TSS trends at undeveloped sites in the western US could be due to differences in the causes of the changes for undeveloped sites in the northwestern US compared to other undeveloped sites in the western US (Fig. 2Fig. 1)may be due to different changes in land management between these groups of sites (explored in more detail below), but may also be due to o. Other contributing factors could includesuch as differences in the suspended particle-size distributions

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being characterized by SSC and TSS ~~and~~ or different ~~regions having different~~ underlying geology between these groups of sites. These factors may also interact. For example, many of the undeveloped TSS sites are in the northwestern US (Fig. SM-4), underlain by ~~the underlying~~ volcanic and metamorphic geology and have step terrain~~-~~. These geologic features ~~in the northwestern US, coupled with the steep terrain,~~ likely result~~s~~ in streams transporting ~~in~~ larger particle sizes, ~~and~~ a situation

5   where TSS provides less ~~less~~ accurate estimates of sediment~~TSS estimates compared TSS estimates from regions underlain by sedimentary rocks, having predominately finer sediment particle sizes in streams~~.

3.2 Land management changes

Murphy and Sprague (2019) showed that MTC is typically the dominant contributor to trends in concentration for sediment

10   and other water-quality parameters such as nutrients, major ions and salinity. This study, which uses a shorter trend period than Murphy and Sprague (2019), found 83% of the sediment ~~sites~~ trends had larger absolute values of MTC than QTC (Table 3). This pattern held across all land-use categories and most sites individually (Fig. SM-5~~3~~, Table 3), indicating changes in land management typically had a greater influence on sediment transport than changes in the streamflow regime alone. Furthermore, MTCs tended to be negative, mirroring the overall sediment trend (~~Fig. 4~~Fig. 3a). Many studies using a

15   variety of approaches have also shown changes in land management and/or land use/cover to be a major driver of changes in sediment over time (e.g. Lacher et al., 2019; Li et al., 2016; Vogl and Lopes, 2010; Kreiling and Houser, 2016; Gitau et al., 2010; Panthi et al., 2017).

~~About 80% of the SSC trends and 60% of the TSS trends had negative MTCs, suggesting that, at most sites, management~~

20   ~~actions on the landscape likely led to decreases in sediment concentration (Table 3).~~ Changes in MTC, which are analytically changes in the C-Q relationship, are a common tool used by researchers and watershed managers to gauge the influence of conservation practices and management ~~efforts~~changes on water quality. For example, in the highly urban Delaware River Basin in the northeastern US, the Delaware River Basin Commission uses changes in the C-Q relationship as one of several ways to detect "measurable change to existing water quality" (Limbeck et al., 2016). Similarly, Moatar et al. (2017) used C-

25   Q relationships to characterize the effect of changes in point sources on water quality across streams in Europe ~~(Moatar et al., 2017)~~. About 80% of the SSC trends and 60% of the TSS trends had negative MTCs, suggesting that, at ~~most~~many sites, management actions on the landscape may have had the desired effect ~~likely led to~~ of decreasing~~es in~~ sediment concentration in local streams (Table 3).

30   ~~Changes in land use/cover are often proposed as a major driver of changes in sediment over time. Studies that support this hypothesis have used methods such as modelling (Crossman et al., 2013; Naik and Jay, 2011; Nelson and Booth, 2002; Lacher et al., 2019), parsing of water-quality and streamflow records (Li et al., 2016; Wu et al., 2012; Shen et al., 2017;~~

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Sediment trends were moderately to strongly correlated (abs(Tau) > 0.4) with several specific changes in land-use/cover, depending on the predominant land use of the watershed and the sediment parameter (Fig. 5Fig. 4). For the most part, SSC trends were well correlated with several changes in land use/cover change variables, particularly in watersheds that had more anthropogenic and homogenous land uses. For example, SSC trends at urban sites were well correlated with 8 5 variables indicative of urbanization and at agricultural sites SSC trends were well correlated with 10 6 variables characterizing changes in agriculture or moderate development (Fig. 5Fig. 4). Undeveloped and mixed-use sites were well correlated with fewer land-use/cover change variables across the watershed and proximal zone. Note, many of the moderate to strong correlations between potential causal variables drivers of change and SSC trends were not not statistically significant at the 0.05 level due to a variety of reasons, one of which is likely the small number of sites in some of the land-use categories.

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In general, TSS trends were not well correlated with many of the 13 watershed or 12 proximal land-use/cover change variables . One exception was the TSS trend in urban sites that were well correlated with 5 variables describing a mix of urban and agricultural land-use/cover changes in the watershed and proximal zone (Fig. 5Fig. 4). The lack of well-correlated variables may be due more to the uncertainty introduced during TSS determinations (Gray et al. 2000) than as opposed to a true lack of potential causes drivers for of changes in for sediment at these sites. ThoughAlso, sample preparation procedures (Gray et al. 2000) that cause TSS trends to better capture characterize changes in smaller sediment sizes (i.e. silts and clays) compared to SSCas opposed to larger sand-sized sediment may hinder the ability of TSS to capture the effects of conservation practices in a watershed. , and perhaps correlating changes in the concentration of smaller particles with land-use/cover changes is more challenging than somewhat larger, sand-sized sediment, making the correlations between TSS and these variables weak.Several studies have shown conservation practices lead to the preferential settling of coarser material as streamflow slows (White et al., 2007; Lee et al., 2000; Meyer et al., 1995; Bombino et al., 2008). For example, White et al. (2007) showed that forested filter strips are efficient at removing coarse-textured sediment but that small particles (generally clay and smaller) are not affected. Lee et al. (2000) found that trapping efficiencies varied depending on the vegetation type used in vegetative buffers but were highest for coarse sediment. Meyer et al (1995) found that grass hedges trapped nearly all sand-sized sediment but allowed silt and clay-sized sediment through. Bimbino et al. (2008) found decreases in sediment size over a reach that had 3 check dams. Therefore, land management changes aimed at slowing streamflow to control sediment may show less of an effect when TSS (as opposed to SSC) is used to characterize sediment changes in a stream and may be one reason for the weak correlations shown in Figure 4. changes in landscape management may disproportionally

influence a particular size of sediment. Some BMPs, such as retention ponds and check dams in small channels, slow streamflow velocities, which in turn encourages larger sized sediment to drop from suspension. These types of BMPs may have little effect on small, silt- and clay-sized particles. This may be part of the reason TSS trends were not well correlated with many of the land-use/cover variables. Other types of BMPs, such as grass filters, settling ponds and grassed waterways, tend to trap silt and the effect of such installations would likely be captured by TSS and SSC determinations of sediment concentration. Thus, information about BMPs, including type, installation dates, and the density of installations across a watershed provide important information for characterizing their possible effect on sediment nearby or downstream. However, this information is often difficult to obtain and aggregate.

Several studies have compared water quality to land-use/cover characterizations based on the entire watershed and to a more confined riparian or buffer area. For example, Johnson et al. (1997) found that buffer zone characterizations of land use/cover were a better indicator of water quality compared to land use/cover across the watershed; whereas, Sliva and William (2001) and Hunsaker and Levine (1995) found the opposite. In this current study, explicit characterization of land-use/cover changes in the proximal zone typically did not yield more or stronger correlations with sediment trends compared to land-use/cover changes across the entire watershed (Fig. 5Fig. 4). For SSC, more trends were well correlated with land-use/cover changes across the watershed (16 variables) compared to just the proximal zone (10 variables). For TSS, 2 of the watershed variables, compared to 4 of the proximal zone variables were well correlated with TSS trends, and 7 watershed variables compared to 6 proximal zone variables were statistically significant (alpha = 0.05; Fig. 5Fig. 4). Various studies have speculated why riparian/buffer zone characterizations do not necessarily provide more explanatory power given the known importance of riparian zone and near-stream conditions on water quality at a local scale (Hunsaker and Levine, 1995; Johnson et al., 1997; Sliva and William, 2001). In this study, most of the proximal zone land-use change variables that were correlated with the sediment trend were similar to the watershed-based estimates, however, there were some exceptions. For example, the percent change in the percent of agricultural land (row crops and pasture) enrolled in CRP in the proximal zone was well correlated with changes in SSC at agricultural sites, whereas the percent change across the whole watershed was not (Fig. 5Fig. 4).

Some land-use/cover changes correlated with sediment trends in a counterintuitive direction. For example, SSC trends at agricultural and undeveloped sites were positively correlated with the percent change in proximal zone agricultural land in the proximal zone enrolled in CRP (Fig. 5Fig. 4). Only 4 agricultural sites had an increase in CRP and only 1 of these 4 had a corresponding increase in SSC (Fig. 6Fig. 5a). This SSC trend was a small <10%, "as likely as not", increase related to a 200% increase in CRP, suggesting the increase in CRP at this site had little influence on sediment concentration. One undeveloped site had an increase in CRP that was related to an ~25% decrease in SSC (Fig. 6Fig. 5a). Thus, these positive correlations provide little information about the influence of changes in CRP on sediment concentrations in streams because

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~~the results are largely influenced by data from a few sites. A more likely reflection of the effects of CRP on sediment in streams is captured by the weak and slightly negative correlations between the CRP change variables and TSS trends (Fig. 4). Interestingly, while the correlation between TSS trends and the CRP change variables ("Ag land in CRP" and "Watershed in CRP" for the entire watershed and the proximal zone) are very weak or slightly negative (Fig. 5Fig. 4), the relationship of percent change in proximal zone agricultural land in the proximal zone enrolled in CRP ("Ag land in CRP") to TSS trends is likely a more accurate reflection of the effects of CRP on sediment concentrations in rivers (Fig. 6Fig. 5b).~~

Typically, process-based watershed models (such as SWAT) are used to assess the effectiveness of conservation practices on water quality because identifying these effects empirically has proven challenging. Some work has been done to relate CRP to changes in nutrients on a national scale (Sprague and Gronberg, 2012) but none specifically address sediment. Studies on the effects of CRP enrolment in individual watersheds give mixed results. Lizotte et al. (2012) found decreases in sediment in an oxbow lake related to the implementation of BMPs and CRP enrolment in the surrounding drainages. Cullum et al. (2010) found conversion of cropped land into forested CRP land in the drainage surrounding an oxbow lake reduced the sediment load entering the lake by an order of magnitude. However, Davie and Lant (1994) found CRP enrolment influenced sediment erosions rates but not sediment loads downstream. They suggest that the location of CRP near the stream may be important for effecting downstream sediment load. In support of this idea, the percent change in CRP enrolment in proximal zone agricultural land was well correlated with SSC trends at agricultural and undeveloped sites, albeit in a counterintuitive direction (Fig. 4). This relationship is largely driven by a handful of sites with decreases in SSC and CRP (Fig. 5a) and gives limited insight. A more likely reflection of the effects of CRP on sediment in streams is captured by the weak and slightly negative correlations between the CRP variables and TSS trends (Fig. 4). Figure 5b shows increases in CRP are typically associated with decreases in TSS. This relationship ~~Many agricultural and non-agricultural sites with TSS data showed increases in CRP and most were associated with decreases in TSS (Fig. 6Fig. 5b). This~~ provides ~~evidence, though limited,,~~ ~~though limited,~~ that increases in CRP land in ~~the proportion of the agricultural land in~~ the proximal zone ~~enrolled in CRP~~ may lead to decreases in sediment concentration in nearby streams. The ~~two~~ undeveloped sites ~~had a~~ with substantial ~~percent~~ increases in TSS ~~associated~~ and ~~with a very~~ large percent increases in CRP (~~Fig. 6~~Fig. 5b)~~ are located~~ ~~Both sites are undeveloped watersheds~~ in the northwestern US and have some of the lowest sediment concentrations in the dataset (e.g. between 3-7 mg/L in 1992) and increased by only 2 or 3 mg/L. Decreases in sediment concentration also appear to be related to how much land in the watershed was enrolled in CRP at the beginning of the trend period. When more than 2% of a watershed was enrolled in CRP in 1992, sediment almost always decreased by 2012 (~~Fig. 6~~Fig. 5c and d), which suggests several potential causes including long lag times between vegetation/soil health improvements and water-quality recovery, that 1992 CRP ~~enrollment~~enrolment represented a commitment to better farming practices by the land owner, or that ~~enrollment~~enrolment in CRP across the watershed needs to be above a certain threshold for effects of these changes to be seen as changes in riverine sediment transport. ~~Not surprisingly, this relationship was most obvious for agricultural sites,~~

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~~since urban, mixed-use and undeveloped sites likely have other land-use/cover or land-management changes driving changes in sediment concentration..~~

Some of the ~~largest~~ strongest correlations occurred between sediment trends and changes in urbanization land-use/cover variables at urban sites (~~Fig. 5~~Fig. 4). ~~Increases in low-medium density dwellings likely indicate additional or new construction and earthmoving activities on previously less developed lands. This c~~Construction related to urbanization disrupts the landscape, increases erosion and often leads to degraded water quality as larger quantities of sediment are transported to the stream. For example, increases in low-medium density dwellings likely indicate additional or new construction and earthmoving activities on previously less developed lands. The MTC and the SSC trend both have a similar relationship to changes in low-medium density dwellings (Fig. 6a and 6c) whereas QTC does not (~~Fig. 7~~Fig. 6e). ~~This finding suggests that changes in the number of low-medium density dwellings may have led to large shifts in the C-Q relationship (the MTC) but had little to no effect on the streamflow regimeThus, t~~The relationship between low-medium density dwellings and the QTC is more muted compared to the MTC, indicating changes in low-medium density dwellings appear to affect overall sediment concentrations more strongly via changes in the C-Q relationship compared to changes in the streamflow regime. Interestingly, despite continued urbanization and increases in some land uses often associated with worsening water quality, sediment concentration still largely decreased at urban sites (~~Fig. 3~~Fig. 2b). For example, increases in SSC only occurred at sites where low-medium density dwellings increased by 30% or more (~~Fig. 7~~Fig. 6). Conversely, ~~At other sites, s~~small and moderate increases in low-medium density dwellings occurred at sites with decreases or little change in SSC. Some of this success ~~may~~could be due to the implementation of ~~best management practices~~BMPs at construction sites. BMPs ~~est management practices~~aimed at preventing erosion and controlling eroded sediment, such as silt fencing, outlet protection, check dams, covering disturbed surfaces, diverting runoff and creating dewatering areas. ~~Thus, these, suggesting conservation best management practices efforts~~ efforts aimed at ~~to reducinge~~ sediment runoff to streams, may be successful, up to a point, at reducing sediment runoff to streams even as lands continue to be urbanized. This effect is less apparent for most undeveloped sites where there has been little change in low-medium density dwelling (clustering of points around x=0) but still substantial decreases in SSC (Fig. 6).

Sites with undeveloped or mixed-use watersheds provided limited insight on potential drivers of ~~changes in sediment~~change, depending on the parameter. SSC trends at these sites were positively related to several land use/cover changes known to result in distributed land, such as increases in cropped land, all developed land, and semi-developed land (Fig. 4). Yet, as a group, undeveloped sites had some of the largest and most consistent decreases in SSC (Fig. 2) despite correlations with land disturbing land use/cover variables, a pattern also observed for SSC sites with urban and agricultural watersheds. However, the SSC changes at mixed-used sites are less consistent and potential drivers of change are less clear. The cluster of increasing TSS concentrations in the northwestern US are notable compared to TSS trends in other geographic regions (Fig.

1); the median increase in TSS for these sites is 18%, the highest of any geographic region for both TSS and SSC (Fig. 2))
and . Tthese northwestern TSS sites also tend to be undeveloped (Fig. SM-4). and, cConceptually, potential drivers of these
sediment increases could be increases in developed land, increases in timber and decreases in forest cover. However, these
variables were not well correlated with TSS trends at undeveloped or mixed-use sites (Fig. 2). and tThis may partially be
because temporally and spatially consistent data on forest cover and timber are only available beginning in 2001 and 1999,
respectively (Falcone, 2017).

3.3 Hydro-climatic changes

The QTC provides a general estimate of the amount of change in sediment due exclusively to changes in the streamflow
regime. When the QTC is large, in absolute terms, natural or human activities could be causing these changes. For example,
systematic changes in climate due to increased greenhouse gases in the atmosphere, quasi-periodic fluctuations in climate
(such as the El Niño-Southern Oscillation), changes in dam operations or extensive alteration of the stream channel (e.g.
straightening or channelization), could all induce a change in streamflow over time, which in turn could lead to changes in
transport, resuspension and erosion of sediment within the channel, riparian zone and floodplain. Using a slightly longer
trend period, Murphy and Sprague (2019) found sediment trends, compared to other water-quality parameters, were more
likely to be comprised of contributions of both MTC and QTC, meaning effects from both changes in management and the
streamflow regime. Similarly, this study finds around 60% of the sites had non-negligible QTC contributions (> +/- 5%
change) to sediment trends (Table 3). These contributions tend to be much smaller than MTCs (Fig. 4Fig. 3a) and only about
17% of the sites had a QTC that exceeded the MTC (Table 3). At a limited number of sites, changes in streamflow
accounted for almost the entire change in sediment (10% of SSC sites and 20% of TSS sites; Table 3), though many of these
sediment trends were small. Only 1 of the SSC trends and 10 of the TSS trends had both an increase (or decrease) of at least
5% that was almost entirely due to changes in the streamflow regime with little to no contributions from changes in land
management. Thus, while changes in the streamflow regime were typically not the dominant driver of changes in sediment
concentration, they were often a contributing influence and at a few sites were the main driver of change (Fig. SM-3).

The correlative strength of hydro-climatic changes with sediment trends across land-use categories and parameters was not
uniform (Fig. 5Fig. 4). At undeveloped sites, Nnone of the hydro-climatic variables were well correlated with sediment SSC
trends and only 2 streamflow trend variables had significant but low magnitude correlations, at undeveloped sites for either
parameter suggesting that climate change and climate variability alone were not sufficiently strong to affect sediment
concentrations across these sites. There is limited consensus on how changes in climate thus far have influenced sediment in
rivers (see references in Whitehead et al. (2009) and Wohl (2015)). Previous models have suggested that changes in climate
will lead to increases and decreases in sediment in particular rivers or areas of the western US (Records et al., 2014; Ficklin

~~et al., 2013).~~ However, human influences, especially dam construction and management, have been shown to be important drivers of change in other areas (Walling, 2009; Rossi et al., 2009; Williams and Wolman, 1984). Surprisingly, the results in this study suggest a limited influence from dams on sediment trends. Changes in the storage capacity of major dams and changes in the number of dams in the watershed were only well correlated with sediment trends at urban sites (~~Fig. 5~~Fig. 4) ~~only~~ — ~~only~~ 2 sites showed a change in either variable, both of which had small (~7%) or moderate (~25%) increases in sediment. However, neither site was close to a dam (both >5 km downstream of a dam) and these increases in the number of dams and dam storage may be occurring much farther upstream from the site. In fact, only 7 and 10 sites with SSC and TSS data, respectively, were within 5 km downstream of a dam. Also, the direction of the sediment trends at these handful of sites were mixed, and across all sites the number of dams and dam storage volume only increased ~~only~~ between 1992 and 2012 (i.e. no site in this dataset had a decrease in the number of dams or amount of storage in the watershed). Thus, the limited effect of dams on sediment trends that was observed in this study is likely because the characteristics of this dataset and the included sites are not optimal for exploring the effect of dams in detail. Additional work explicitly considering sites closer to dams and information such as dam proximity, the proportion of total streamflow controlled by dams and trapping efficiency of upstream dams would further illuminate this potential driver of change.

Variables characterizing trends in specific annual metrics of daily streamflow ("Q Slope: mean day", "Q Slope: max day", and "Q Slope: 7-day min") had a few moderate correlations with sediment trends (~~Fig. 5~~Fig. 4). However, ~~T~~the QTC estimates indicate stronger influences from changes in the streamflow regime ~~on sediment trends~~ (Table 3) than is apparent from the correlations with the sediment trend ~~correlation analysis~~ (~~Table 3~~Fig. 4). When the correlation analysis ~~is~~was repeated using QTC instead of the sediment trend, often 1 or 2 of the streamflow trend variables are well correlated with QTC in each of the land use categories (Fig. 7d), indicating that changes in the streamflow regime are influencing sediment concentrations but these changes are largely being masked by changes in concentration due to ~~watershed~~land management (MTC).~~It is possible the hydro-climatic change variables associated with streamflow were not strongly correlated with sediment trends because changes in the streamflow regime were masked or offset by larger coincident changes in land management.~~ This effect was also seen for other water-quality parameters ~~as well~~ in Murphy and Sprague (2019). Figure 7 demonstrates this effect by comparing bivariate plots of the sediment trend, MTC and QTC to a land-use change variable and hydro-climatic change variable. The sediment trend is not well correlated with a change in annual mean daily streamflow (Fig. 6b). However, the well-defined positive relationship between mean daily streamflow and the QTC indicates that ~~large~~ increases or decreases in streamflow relate ~~to large decreases~~ to corresponding increases or decreases in sediment concentration ~~when changes in mean daily streamflow are compared to just the QTC there is a well-defined positive relationship indicating that large decreases in streamflow relate to large decreases in sediment concentration and the same for positive or increasing changes~~ (~~Fig. 7~~Fig. 6f). This pattern is quite different from when the percent change in low-medium density dwellings is compared to the sediment trend, MTC and QTC. These relationships suggest that decreases in

streamflow also decrease sediment transport or resuspension in the stream, but these improvements are partially offset by human activities in the watershed, such as increases in low-medium density dwellings. Thus, the lower correlations shown in Figure 4 may be downplaying the importance of changes in the streamflow regime on sediment trends.

5   An additional consideration is that changes in streamflow can also induce a change in the C-Q relationship, and this response may be more common for sediment compared to other water-quality parameters. Recall the MTC captures the influence of changes in the C-Q relationship on sediment concentration, thus if the streamflow regime changed in such a way to perturb the C-Q relationship this effect would be captured by the MTC. C-Q relationships have been shown to vary by storm depending on a host of hydrologic and antecedent conditions, and over short time periods due to droughts or highly wet
10 years (Duncan et al., 2017; Biron et al., 1999). However, sustained, systematic changes in the C-Q relationship due exclusively to changes in the streamflow regime are less well documented (e.g. Bieroza et al., 2018). A few of the hydro-climatic change variables were well correlated with MTC, though again, only at urban and agricultural sites (Fig. 8Fig. 7b). This finding suggests the limited ability of hydro-climatic changes to systematically shift the C-Q relationship over time, at least for sediment concentrations at these sites. QTC was much more strongly correlated with hydro-climatic change
15 variables (Fig. 7d), compared to land use/cover variables (Fig. 7c), across all land-use categories and for both sediment-sample types (Fig. 8Fig. 7), showing the importance of changes in streamflow on sediment, even if these changes are often masked or counteracted. Understanding the sensitivity of the C-Q relationship (i.e. the MTC) to systematic changes in the streamflow regime would further illuminate the effects of such changes on sediment concentration in rivers and streams.

20 **3.4 Importance of location**

Sediment dynamics are strongly influenced by geographic location and are particularly sensitive not only to land use of the watershed, floodplain and riparian zone but also the geologic, pedologic, climatologic, physiologic, hydrologic and geomorphologic conditions of the site (Charlton, 2007). The location of a sampled site in a fluvial system's longitudinal profile can be an important factor in the types and amounts of sediment available for transport, particularly if that stretch of
25 river is supply-limited or transport-limited. Similarly, channel evolution processes are an important determinant of sediment dynamics. For example, if a site is located on or downstream of a length of river that shifts from an aggradation to degradation phase this would change sediment concentrations over time. Gellis et al. (1991) found that decreases in sediment and salt loads in the Colorado River basin were likely due to a natural shift in incised-channel evolution, which includes sequential phases involving channel deepening, widening and then deposition of a floodplain. Changes in sediment loads
30 related to this natural geomorphic process were further exacerbated by concurrent changes in the streamflow regime (Gellis et al., 1991). These natural factors can influence not only a site's capacity for change but also its recovery potential (Charlton, 2007). Multiple static and long-term watershed conditions (Table 1) were used to explore the sensitivity of

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sediment trends to location. Surprisingly, only a few of the land-use categories had sediment trends that were well correlated with one or more of the ~~18~~20 static/long-term watershed characteristics, again more so for SSC trends than TSS trends (~~Fig. 5~~Fig. 4). Since the sediment trends were in terms of absolute change for these correlations, positive (negative) correlations indicate increased (decreased) sensitivity of sediment concentrations at a site as the gradient of a given static/long-term

5   watershed characteristic increases, leading to larger (smaller) sediment trends. For example, SSC trends at undeveloped sites were negatively correlated with long-term relative humidity, indicating smaller changes in sediment (increases or decreases) occurred at sites with higher relative humidity. Sites with high relative humidity tend to also be more vegetated and the amount of sediment readily available for transport at these sites is less than at a more arid site. Thus, SSC at more arid sites is more sensitive to hydrologic or land-management changes than at humid sites.

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The MTC and QTC estimates suggest location is important for understanding the potential drivers of change in sediment concentration. When grouped broadly by geographic region, western US sites, which also are often undeveloped (Fig. SM-~~4~~2), typically have negative QTCs for both SSC and TSS trends, indicating changes in streamflow tend to lead to decreases in sediment in this region (~~Fig. 4~~Fig. 3b and ~~Fig. 4~~Fig. 3c). Furthermore, ~~western US sites also appear to cluster according to~~

15   ~~whether the QTC and MTC have the same or opposing signs, which indicates whether streamflow enhanced or offset the~~ ~~effects of concurrent changes in land management on sediment. For~~ decreasing SSC trends at western sites~~,~~ typically have negative MTCs coupled with somewhat smaller but also negative QTCs~~,~~ suggest~~ing~~ changes in the streamflow regime further enhanced larger decreases in sediment from changes in land management (~~Fig. 4~~Fig. 3b). For increasing TSS trends at western sites, positive MTCs coupled with somewhat smaller negative QTCs suggest the opposite; changes in streamflow

20   partially offset potential increases in sediment due to changes in land management (~~Fig. 4~~Fig. 3c). This opposing effect results in somewhat smaller sediment trends than would have been observed if the streamflow regime had remained stationary over this period. An example of opposing MTC and QTC ~~having opposing directions~~ at a single site is given in Murphy and Sprague (2019). In ~~T~~t~~hat~~his example, SSC in ~~on~~ the Skunk River (~~in~~ Iowa, US)~~US, SSC~~ had a -90% MTC and 20% QTC giving an overall decrease of -70% in ~~SSC~~sediment concentration. The negative MTC ~~change~~ was attributed to

25   transitioning erodible land out of production ~~while~~which likely decreased the amount of available sediment for transport. The positive QTC was attributed to increases in spring and summer streamflow over this same period which likely lead to increased mobilization of sediment to the stream, partially offsetting the improvements shown by the MTC.~~.~~

Central and eastern US sites show a mix of opposing and reinforcing effects of the MTC and QTC on sediment trends (~~Fig.

30   4~~Fig. 3b and ~~Fig. 4~~Fig. 3c). For both parameters, ~~roughly~~ about half the sites had opposing effects and the other half had reinforcing effects on the sediment trend (Table 3; Fig. SM-~~5~~3). However, it was relatively rare for both the QTC and MTC to be positive, indicating it was uncommon for increases in sediment to be due to increases from both changes in land management and changes in streamflow. Instead, increases from changes in land management were more often slightly

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offset by decreases from changes in the streamflow regime (negative QTCs; ~~Fig. 4~~Fig. 3b and ~~Fig. 4~~Fig. 3c). Finally, the QTC was near zero for about half of TSS trend sites (Table 3), largely in the eastern US (~~Fig. 4~~Fig. 3c)~~., unlike SSC trends where fewer sites had QTCs near zero (Fig. 4Fig. 3b).~~ Since TSS trends tend to _not_ capture changes in ~~a finer~~ coarser suspended ~~particle-size distribution than SSC~~sediment (as compared to SSC), it may be that TSS trends are less sensitive to changes in the streamflow regime, particularly when these changes occur at higher streamflow, which has been observed in many rivers in the eastern US (e.g. Armstrong et al., 2014). ~~Compared to the QTC, it was much less common for the MTC to be near zero, especially when changes in SSC or TSS were moderate to large in magnitude (Fig. 4Fig. 3b and Fig. 4Fig. 3c). Only 1 SSC trend and 10 TSS trends had a change in sediment that was greater than +/- 5% and the MTC was near zero, indicating that at select sites, changes in sediment were almost exclusively due to changes in the streamflow regime (Table 3).~~

3.5 Limitations and Outlook

In many ways, the datasets used here provide a greater breadth and depth of information for exploring potential causes of sediment trends compared to previous studies: the datasets are temporally consistent thus comparable over time; spatially consistent allowing for comparison across sites; publicly available with well-documented metadata; and spatially explicit allowing for estimates of the ~~entire~~ watershed ~~or~~ and the proximal zone (Falcone, 2017). However, even with this extensive information, it was difficult to identify specific potential ~~causes~~ drivers of sediment trends for some land-use categories. Additionally, because multiple correlations were completed (~~208~~136 for each set of SSC and TSS trends shown in ~~Fig. 5~~Fig. 4), about 2 and ~~10~~7 of the statistically significant correlations at the alpha 0.01 and 0.05 level, respectively, can be expected to be false positives.

The difficulty of establishing clear, straightforward relationships between potential ~~causal variables~~ drivers of change and sediment trends presents a real challenge for researchers, especially those working with streams across a large geographic region. It is possible the choice of potential causal variables used in these analyses did not capture the relevant changes at these sites. Other variables, if available, may better characterize important changes on the landscape or ~~to~~ in ~~watershed~~ land management. There is quite possibly a disconnect between the conceptual "land-management changes" identified while parsing the sediment trends and the land-use/cover change information that was available for the correlation analysis. Information that could be helpful but often is not available in a nationally or temporally consistent dataset include channel and floodplain geomorphological characteristics, construction activities near the site, types and density of riparian vegetation, BMP information, changes in dam operations and if the site is undergoing channel evolution and what phase the site is in (i.e. degradation or aggradation).

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Additionally, tThe use of TSS to characterize changes in sediment may make exploring potential causes more difficult than when SSC is used. As described in Section 2.1, TSS tends to measure the concentration of smaller suspended particle sizes as opposed to the entire suspended particle-size distribution of a sample and has been "shown to be fundamentally unreliable for the analysis of natural-water samples" (Gray, et al., 2000). The uncertainty inherent in TSS estimates is a likely

5   explanation for the lack of correlation between TSS trends and potential causal variables (Fig. 5Fig. 4). However, heterogeneity across the sites and difficulty in identifying potential causes of change in only the fine suspended-sediment fraction (less sands) are other possibilities. TSS and SSC trends can also give quite different results. In Murphy et al. (2018), 5 sites with 2002-2012 trends and 3 sites with 1992-2012 trends had both types of sediment data. These trends had different magnitudes, and a few had different trend directions depending on the sediment parameter (Fig. SM-64), which supports the

10 conclusion of the incompatibility of SSC and TSS estimates as shown by Gray et al. (2000). Thus, caution should be taken when comparing TSS and SCC results and researchers should note the possible difficulties when using TSS estimates to understand changes in sediment and their potential drivers.

Finally, Additionally, sediment may present a relatively unique challenge when trying to identify potential causes drivers of

15 trends compared to other water-quality parameters, such as pesticides or nutrients. Sediment transport is fundamentally different from other water-quality parameters, relying on the physical properties of fluid dynamics as opposed to chemical reactions. For example, streambank erosion can be a dominant contributor of suspended material to a river, and while adjacent land use/cover and management can be important in determining the amount of erosion (Fox et al., 2016), it is also possible that channel erosion is more strongly related to channel properties and conditions, such as channel roughness, slope,

20 sinuosity and near-channel vegetation density and type (Charlton, 2007). Changes in these variables are difficult to track over time and a unified dataset containing such information for multiple sites across a specific geographic region or the US is non-existent. Also, the source and mobilization of sediment can be natural or human-influenced and includes the remobilization of legacy sediment (Wohl, 2015). Changes in land management may have led to the deposition of sediment stores in the channel and floodplain, but a change in the streamflow regime may be the ultimate factor causing the erosion

25 and transport of the stored sediment downstream. Lastly, the causes of changes in sediment transport vary based on the time scale. For example, changes occurring within a single decade are more strongly related to weather patterns compared to changes occurring over centuries, which are more strongly related to tectonics (Vercruysse et al., 2017; Charlton, 2007).

Next directions for better understanding drivers of sediment trends include practical activities, such as continued high-quality

30 sediment monitoring, the maintenance of current river monitoring networks, and the development and maintenance of datasets that describe likely drivers of change. This analysis identified some important gaps in available explanatory datasets—like the lack of a long-term dataset that describes forest cover and timber across the US. Next directions also include conceptual developments focused on the use of improved methods for linking changes in river sediment with

potential drivers of change and considering the interconnected ways changes in the streamflow regime influence C-Q relationships. This will include drawing on techniques from other scientific fields, such as epidemiology, that also collect and analyse longitudinal observational data. Finally, though many of the 137 sites across the US saw decreases in sediment, this analysis also showed that sediment concentration readily responds to changes in streamflow. Thus, decreases in sediment from conservation practices and BMPs will need to be commensurate with projected changes in climate and its subsequent effects on the hydrologic cycle.

4.0 Conclusion

Annual mean concentrations of suspended sediment largely decreased between 1992 and 2012 at 137 stream sites with watershed areas < 300,000 sq km across the contiguous US. Many of these decreases occurred at sites with some of the highest concentrations and at sites that drained watersheds with concurrent small to moderate increases in human-related land uses (i.e. urban and agricultural land uses), suggesting efforts to minimize sediment pollution to streams and rivers may be having the desired effect in some places. A notable exception to these decreases is a cluster of increasing TSS concentrations at undeveloped sites in the northwestern US. At ~~many locations~~83% of sites, a change in land management (including changes in land use/cover), as opposed to a change in the streamflow regime, was the primary contributor of changes in sediment, though systematic changes in the streamflow regime ~~often~~ had a mild-to-moderate influence on sediment at 66% of SSC sites and 57% of TSS sites (Table 3). Across all sites, the median MTC was -23% and -10% for SSC and TSS trends, respectively, compared to the median QTC of -4% (SSC) and -3% (TSS) (Fig. 3). The influence of specific hydro-climatic changes on sediment trends appears to be masked due to more influential changes in land management. ~~Surprisingly, characterizing land-use/cover changes in the proximal zone provided little additional information compared to characterizing land-use/cover changes across the whole watershed, indicating a need for more precise information about near-channel conditions.~~ Sediment trends determined using TSS data were weakly correlated with potential causal variables, highlighting the difficulty of using TSS, as opposed to SSC, ~~data~~ to infer potential causal relationships largely due to the unreliability of TSS for characterizing stream water quality but also differences in suspended particle size distributions. While identifying the specific land use/cover or hydro-climate changes responsible for these sediment decreases remains a challenge, the strongest correlations tended to occur at sites with more homogenous, human-related land uses (i.e. agricultural and urban lands). At many sites, across all land-use categories, decreases in sediment are likely due to changes in land management with changes in the streamflow regime providing a limited though important and often overlooked influence.

Data availability

Site information and the sediment concentration and streamflow data used to estimate the trends are published at http://dx.doi.org/10.5066/F7KW5D4H (De Cicco et al., 2017), the land use data are available at https://doi.org/10.5066/F7TX3CKP (Falcone, 2017), the streamflow trend data are available at

5 http://www.dx.doi.org/10.5066/F7D798JN (Farmer et al., 2017), and the estimates of the sediment trends, management trend components (MTC) and streamflow trend components (QTC) are available at https://doi.org/10.5066/F7TQ5ZS3 (Murphy et al., 2018).

Author contribution

10 Jennifer Murphy was the sole contributing author and completed the data processing, ~~and~~ analysis and report writing.

Competing interests

I have no competing interests.

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Table 1. Potential causal variablesLand use/cover and hydro-climatic change variables and static/long-term watershed characteristics used in correlation analyses. Streamflow trend variables ("Q slope: mean day", "Q slope: max day", and "Q slope: 7-day min") are from Farmer et al. (2017); all other variables published in Falcone (2017), see publications for details and original

source information. ## and #### symbols in variable names indicate 2-digit or 4-digit year of data value. Percent-change computations are (trend end -year value - trend start -year value) / trend start -year value * 100, using years closest to 1992 and 2012, unless otherwise noted. [square ~~kilometer~~kilometre, sq km; meters, m; ~~centimeters~~centimetres, cm; degrees ~~Celscius~~Celsius, °C]

Short name	Data description (original time-series or static variable name from referenced source)
~~Watershed LLand~~ use~~/ and land~~ cover changes ~~across entire watershed or proximal zone[1]~~	
Agricultural land	Percent change in agricultural land, excluding potential grazing lands, as a percentage of the watershed (NWALT##_AG4344_SUM) ~~or proximal zone (RIP_NRSITE_NWALT##_AG4344_SUM)~~
Ag+Grazing land	Percent change in agricultural land, including potential grazing lands, as a percentage of the watershed (NWALT##_AG4346_SUM) ~~or proximal zone (RIP_NRSITE_NWALT##_AG4346_SUM)~~
Cropped land	Percent change in row-cropped land as a percentage of the watershed (NWALT##_43) ~~or proximal zone (RIP_NRSITE_NWALT##_43)~~
Ag land in CRP	Percent change in proportion of agricultural land enrolled in the Conservation Reserve Program (CRP) across the ~~entire~~ watershed (crp.crop##) ~~or proximal zone[2] (RIP_NRSITE_CRP_CROP##)~~
Watershed in CRP	Percent change in amount of land enrolled in CRP as a percentage of the watershed (NWALT##_AG4344_SUM * crp.crop## * 0.01) ~~or proximal zone (RIP_NRSITE_NWALT##_AG4344_SUM * RIP_NRSITE_CRP_CROP## * 0.01)~~
Proximal zone ag land in CRP	Percent change in proportion of agricultural land enrolled in the Conservation Reserve Program (CRP) in the proximal zone[2] (RIP_NRSITE_CRP_CROP##)
Proximal zone in CRP	Percent change in amount of land enrolled in CRP as a percentage of the proximal zone (RIP_NRSITE_NWALT##_AG4344_SUM * RIP_NRSITE_CRP_CROP## * 0.01)
All developed land	Percent change in developed and semi-developed land as a percentage of the watershed (NWALT##_DEV_SUM + NWALT##_SEMIDEV_SUM) ~~or proximal zone (RIP_NRSITE_NWALT##_DEV_SUM + RIP_NRSITE_NWALT##_SEMIDEV_SUM)~~
Developed land	Percent change in developed land as a percentage of the watershed (NWALT##_DEV_SUM) ~~or proximal zone (RIP_NRSITE_NWALT##_DEV_SUM)~~
Semi-developed land	Percent change in semi-developed land (land in close proximity to developed lands and partially used for the same purposes) as a percentage of the watershed (NWALT##_SEMIDEV_SUM) ~~or proximal zone (RIP_NRSITE_NWALT##_SEMIDEV_SUM)~~
Impervious area	Percent change in impervious land cover as a percentage of the watershed (NWALT_IMPV##) ~~or proximal zone[2] (RIP_NRSITE_NWALT_IMPV##)~~
Low-med density dwellings	Percent change in land with low-medium density residential development as a percentage of the watershed (NWALT##_26) ~~or proximal zone (RIP_NRSITE_NWALT##_26)~~
Low-use land	Percent change in land with little to no development or agriculture as a percentage of the watershed (NWALT##_50 + NWALT##_60) ~~or proximal zone (RIP_NRSITE_NWALT##_50 + RIP_NRSITE_NWALT##_60)~~
~~Mining & related activities~~Forest since '02	Percent change in ~~mined~~ forested land between 2002 and 2012 as a percentage of the watershed (~~NWALT##_41~~CDLXXXX_PCT_141 + CDLXXXX_PCT_142 + CDLXXXX_PCT_143) ~~or proximal zone (RIP_NRSITE_NWALT##_41)~~
~~Fracking wells~~Cumulative timber	Cumulative sum of the percent of the watershed with timber or forest cutting for years since 1999 ~~Percent change in the mean number of hydraulic fracturing wells within subwatersheds as a percentage of the watershed~~ (~~frac_wells~~timber_####)
Hydro-climatic changes	
Total precip	Percent change in total precipitation across the watershed (sum of monthly mean precipitation, see Falcone (2018))
Average temp	Percent change in annual mean monthly temperature across the watershed (mean of monthly mean temperature, see Falcone (2018))
Temp range	Percent change in monthly mean temperature range across the watershed (difference between hottest and coldest monthly mean temperature of the same year, see Falcone (2018))
Max temp	Percent change in annual maximum monthly temperature across the watershed (maximum of monthly mean temperature, see Falcone (2018))
Q slope: mean day	Slope of annual mean daily streamflow trend as percent change per year ((e^meanL_slope - 1)*100)
Q slope: max day	Slope of annual maximum daily streamflow trend as percent change per year ((e^maxL_slope - 1)*100)
Q slope: 7-day min	Slope of annual 7-day minimum streamflow trend as percent change per year ((e^min7nL_slope - 1)*100)
Density of major dams	Percent change in the number of major dams per 100 sq km across the watershed (MAJDAMS_100sqkm_####)
Dam storage	Percent change in dam storage per sq km across the watershed (NORMSTOR_sqkm_####)
Static/long-term watershed characteristics	
Drainage area	Drainage area of the watershed, in sq km (gisareakm2)
Basin compactness	Watershed compactness ratio (area/perimeter^2 * 100), higher number means more compact (circular) shape, unitless (bas_compactness)
Average elevation	Mean watershed elevation, in m (ELEV_SITE_M)
Stdev of elevation	Standard deviation of elevation across watershed, in m (ELEV_STD_M_BASIN)
Proportion canals/pipes	Proportion of flowlines that are canals, ditches or pipes, unitless (prop_canals_pipe)
Percent tile drains	Estimate of percent ~~of~~of the ~~watershed drained by tile drains in 2012 (CPRAC_tiledrains)
Percent conservation tillage	Estimate of percent of the watershed with conservation tillage in 2012 (CPRAC_conservation_till)
Percent forest in 2012	Percent of the watershed with forest in 2012 (CDL2012_PCT_141 + CDL2012_PCT_142 + CDL2012_PCT_143)

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Short name	Data description (original time-series or static variable name from referenced source)
Percent proximal zone forest in 2012	Percent of the proximal zone with forest in 2012 (RIP_NRSITE_NLCDXX_FOREST)[2]
Long-term average precip	Mean annual precip for the watershed, using 1981-2010 record, in cm (PPT_AVG_8110)
Long-term average temp	Mean annual air temperature for the watershed, using 1981-2010 record, in C° (T_AVG_8110)
Long-term relative humidity	Mean relative humidity for the watershed, using 1961-1990 record, in percent (RH_AVG)
Base flow index	Base Flow Index, which is the ratio of base flow to total streamflow, in percent (BFI_AVE)
Percent clay	Percent of the watershed with clay soils (CLAYAVE)
Average permeability	Average permeability, in inches per hour (PERMAVE)
Erosion potential (K)	K factor from Universal Soil Loss Equation, higher values = greater potential for erosion, unitless (KFACT_UP)
Era of first dev, watershed	Era of first development, i.e. a measure of if the area was developed a long time ago or recently. Original values from Falcone (2017) converted to decimal decade, e.g. 2000.75 means 1st development accuredoccurred about 3/4 of the way through the 2000 decade (so circa 2007). Note, 1940 means 1940 or earlier. (ERA_FIRSTDEV)
Era of first dev, proximal zone[2]	Same as "Era of first dev, watershed" but calculated only considering the near-site riparian proximal zone (RIP_NRSITE_ERA_FIRSTDEV)
Major dam density in 2013	Number of major dams per 100 sq km across watershed in 2013 (MAJDAMS_100sqkm_2013)
Dam storage in 2013	Dam storage across watershed in 2013, in acre feet per 100 sq km (NORMSTOR_sqkm_2013)

[1]All land-use variables rounded to 1% of the watershed or riparian proximal zone area prior to calculating percent change.

[2]Variables not included in Falcone (2018) and estimated for this study using the same procedures described in Falcone (2018)

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20 **Table 2. SSC and TSS trends from 1992 to 2012. Starting concentration, concentration change and percent change rows show: minimum - maximum (mean), rounded to two significant figures. [SSC, suspended sediment concentration; TSS total suspended solids concentration; n, count; conc, concentration; mg/L, milligrams per liter; %, percent]**

	SSC	TSS
Number of sites	41	99
Starting conc	4.4 - 870 (140)	1.1 - 270 (45)
Conc change (mg/L)	-410 - 72 (-51)	-83 - 40 (-9.1)
Conc % change	-95 - 61 (-25)	-64 - 200 (-6.3)
% change for upward trends	5.8 - 61 (31)	13 - 200 (47)
% change for downward trends	-95 - -11 (-43)	-64 - -8.5 (-31)
% change for uncertain trends	-5.1 - 10 (4.3)	-8.7 - 30 (2.7)
n Upward[1] trends (% of sites)	4 (9.8%)	20 (20%)
n Downward[1] trends (% of sites)	28 (68%)	53 (53%)
n Uncertain[2] trends (% of sites)	9 (22%)	26 (26%)

[1]Includes likelihoods ≥ 0.70 (trend is "likely" and "somewhat likely" upward or downward)
[2]Only likelihoods < 0.70 (trend is "as likely as not" to be upward or downward, i.e. trend direction is uncertain)

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Table 3. Percent and number of sites with SSC and TSS trends for various combinations of ~~estimates of~~ QTC (sediment changes due to changes in the streamflow regime) and MTC (sediment changes due to changes in land management). Recall the sediment trend = MTC + QTC

	SSC sites	TSS sites
MTC > 0 Changes in land management lead to increases in sediment	20% (8)	40% (40)
QTC > 0 Changes in the streamflow regime lead to increases in sediment	~~42~~41% (17)	30% (30)
abs(QTC) ≥ abs(MTC) Changes in the streamflow regime contribute more to the sediment trend than changes in land management	17% (7)	17% (17)
abs(QTC) ≥ 5% Changes in the streamflow regime contribute a non-negligible amount of change to the sediment trend	66% (27)	57% (56)
abs(QTC - sediment trend) ≤ 10% Changes in the streamflow regime account for almost the entire amount of change ~~to the~~ in sediment ~~trend~~	10% (4)	20% (20)
And if, abs(sediment trend) ≥ +/- 5% In addition to abs(QTC - sediment trend) ≤ 10%, the sediment trend shows a non-negligible amount of change over the same period	2% (1)	10% (10)
MTC & QTC have different signs The effects of changes in streamflow regime and changes in land management on ~~the~~ sediment ~~trend~~ oppose each other leading to smaller changes in sediment than either trend component alone	51% (21)	59% (58)
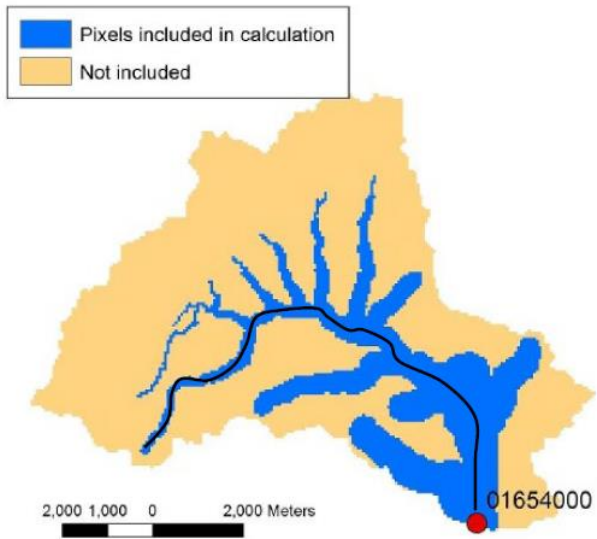
Figure 1. Example of pixels used in near-site near-stream proximal-zone calculation for site 01654000. Calculation of whole watershed values would use the tan and blue areas. Figure originally published in Falcone (2017).

SSC | TSS

Western
Central
Eastern

Likelihood and trend direction

▲ Likely upward   ▼ Likely downward

▲ Somewhat likely upward   ▼ Somewhat likely downward

△ As likely upward as not   ▽ As likely downward as not

Magnitude of percent change

● > 50% change

● 5−50% change

• < 5% change
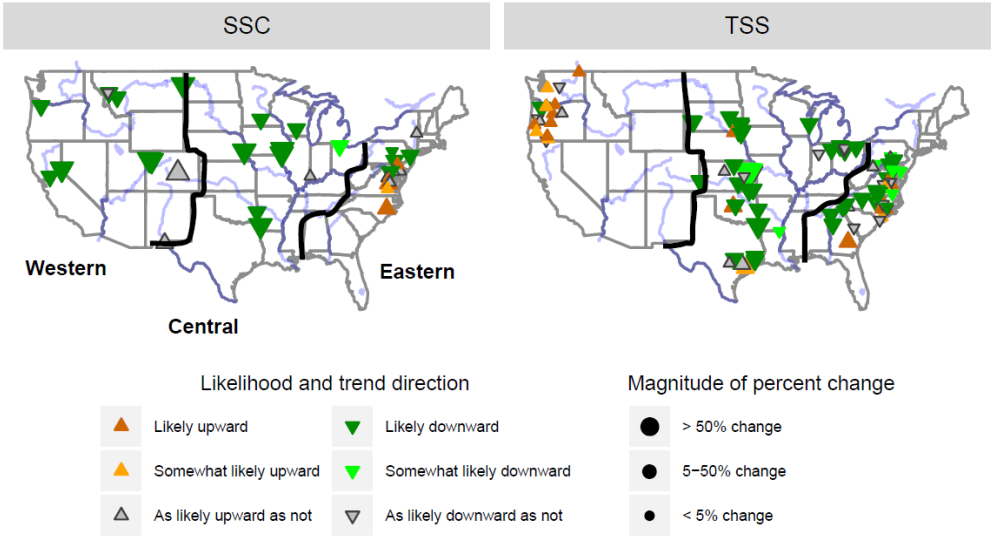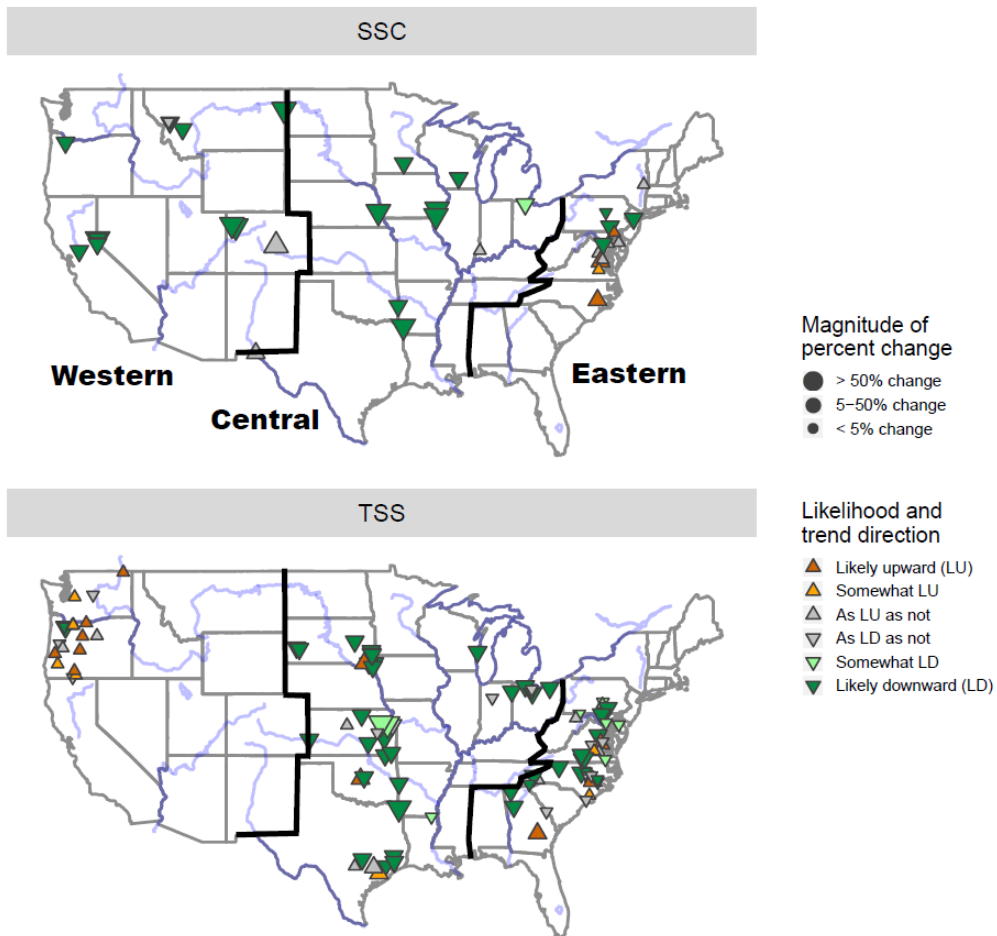
Figure 21. SSC and TSS trends from 1992 to 2012, showing trend direction, likelihood category, and magnitude. Base map generated using ggmap in R statistical software (Kahle and Wickham, 2013).
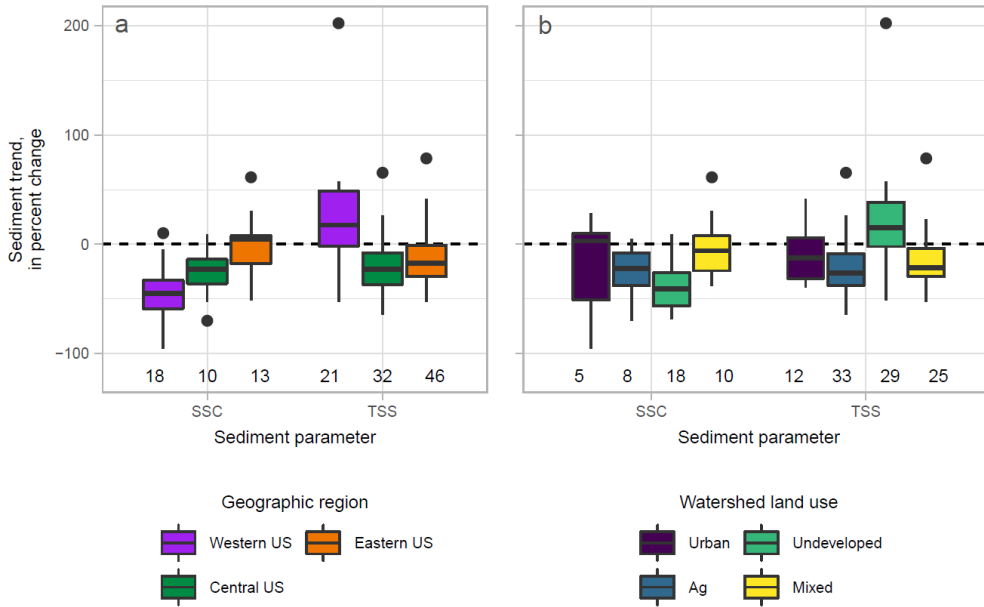
Figure 32. SSC and TSS trends by (a) geographic regions (depicted in Figure 21) or and (b) predominate land use of watershed land use, including all sites and likelihoods. Dashed line denotes 0% change. Numbers above x-axis are site counts. For the boxplots, the top and bottom of the boxes correspond to the interquartile range (25th and 75th percentiles), top and bottom whiskers correspond to 1.5*(interquartile range), and points are data falling beyond 1.5*(interquartile range).
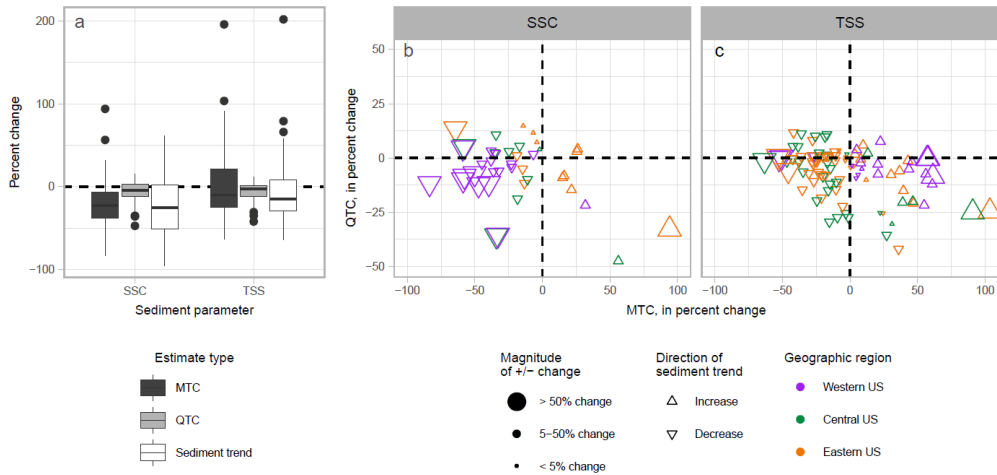
Figure 4~~3~~. (a) Boxplots of sediment trend, MTC and QTC estimates by sediment parameter. See description of boxplots in the caption of ~~Fig. 3~~Fig. 2. (b~~)~~ and (~~c~~) Bivariate plots of ~~the~~ QTC versus MTC for each site by sediment parameter, color coded by geographic region~~s~~ and sized by the magnitude of sediment trend. Note, (b~~)~~ and (~~c~~) plots exclude 1 undeveloped western US site, orBRSS0035, with 195% MTC, 7% QTC and 202% sediment trend. Recall, at a given site, sediment trend = MTC + QTC.
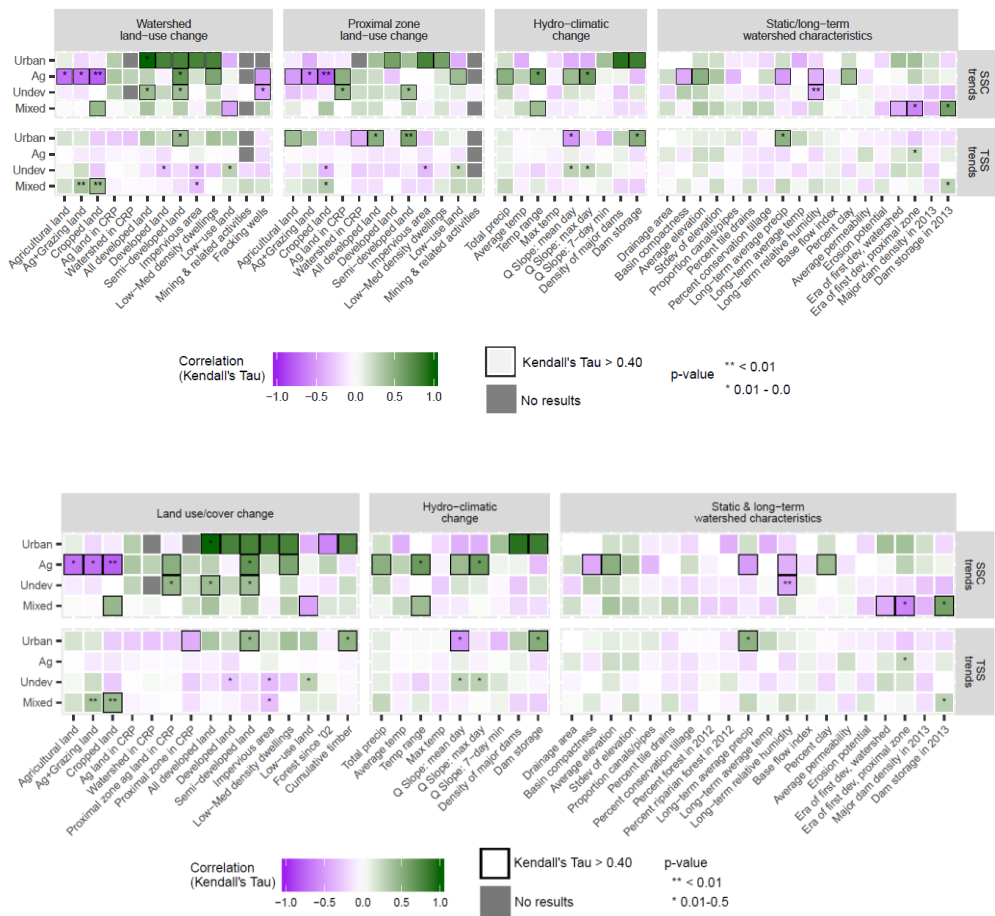
Figure ~~5~~4. Correlations between 1992-2012 sediment trends and various potential ~~causal~~ drivers of change (land use/cover and hydro-climatic ~~variables)~~ variables and static/long-term watershed characteristics, grouped by the 2012 land use of the contributing watershed. Note ~~watershed and proximal zone~~ land -use/cover change variables and hydro-climatic change variables ~~were~~ are correlated with sediment trends in percent change, whereas the static/long-term watershed characteristics were correlated with the sediment trends in absolute percent change.
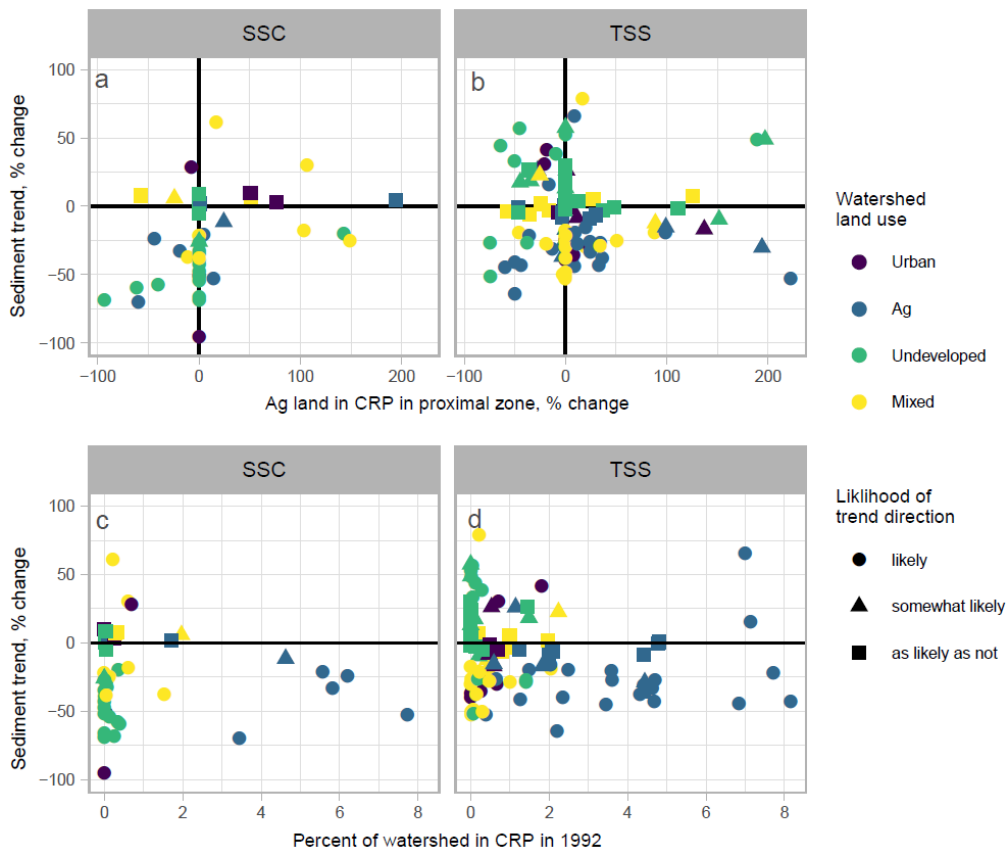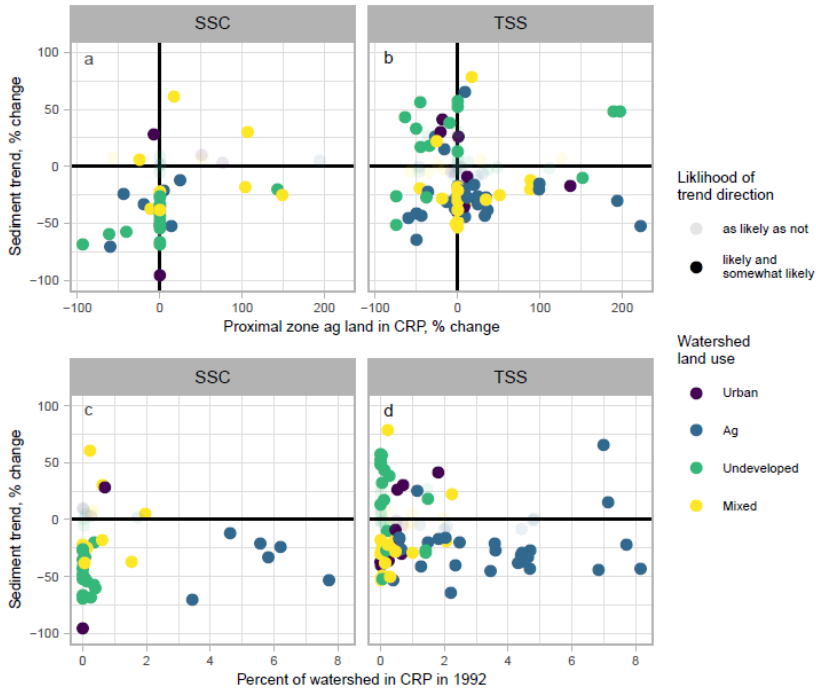
Figure 65. (a) and (b) Sediment trend versus percent change in proportion of agricultural land in the proximal zone enrolled in CRP between 1992 and 2012. (c) and (d) Sediment trend versus percent of land in watershed enrolled in CRP during the trend start year (1992). Note all plots exclude site orBRSS0035 (-200202% increase in TSS and 0% change in CRP).
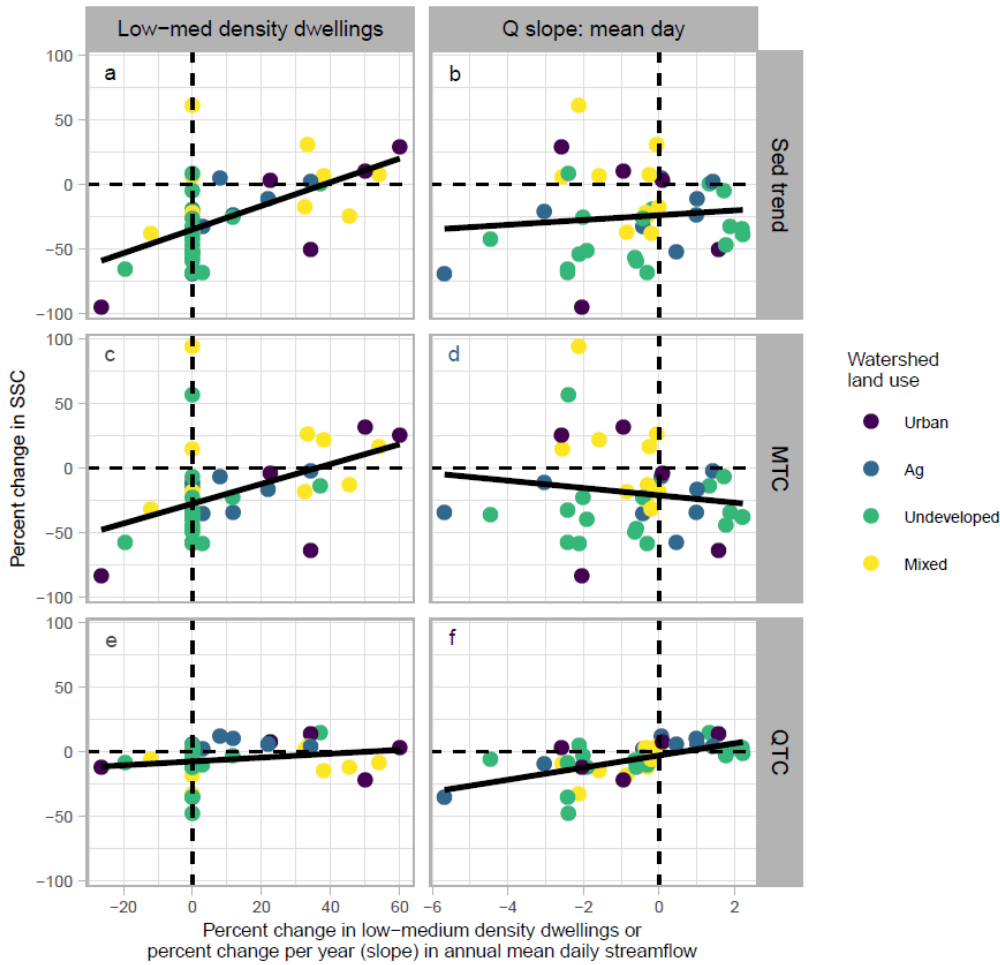
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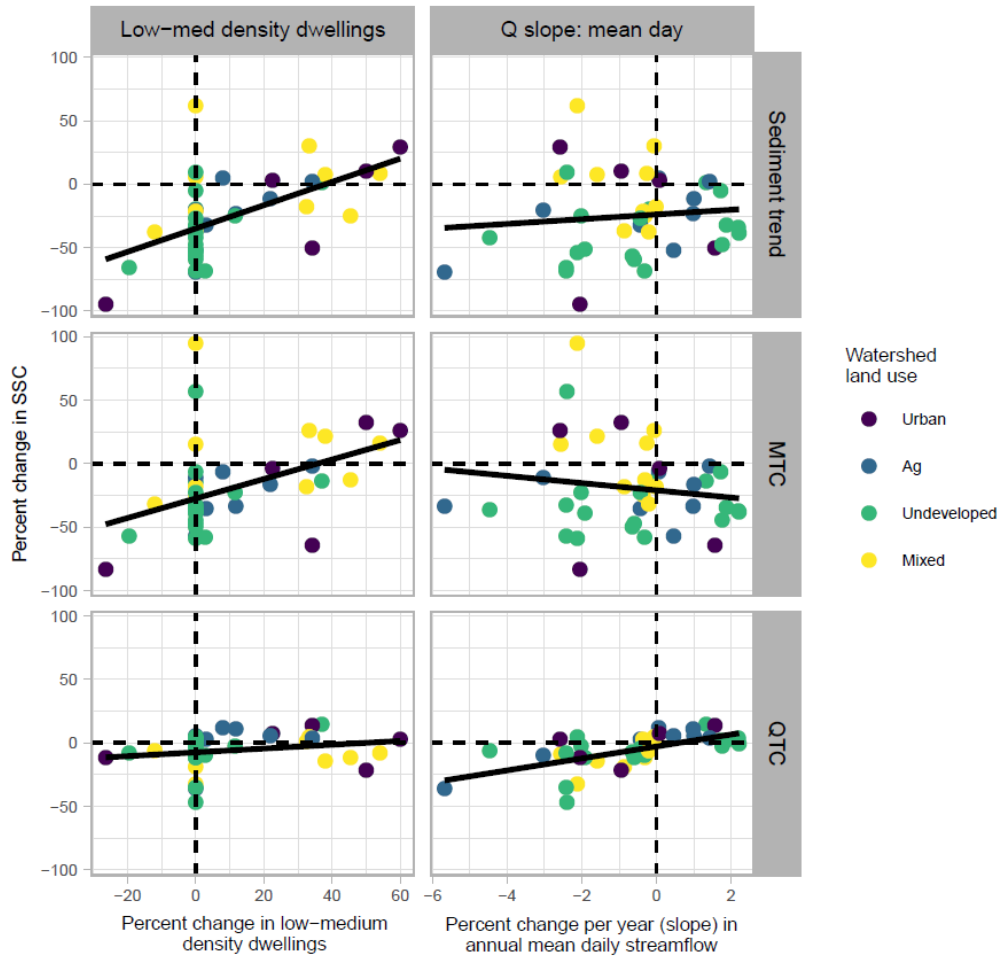
Figure 76. Bivariate plots of the SSC trend (overall change in sediment concentration), MTC and QTC versus two potential causal variables: percent change in the percentage of low-medium density dwellings in the watershed and percent change per year (slope) of annual mean daily streamflow, for the 1992-2012 trend period. Black line is an ordinary least squares regression fit through all the data to show relationship between variables, and dashed lines indicate 0% change.
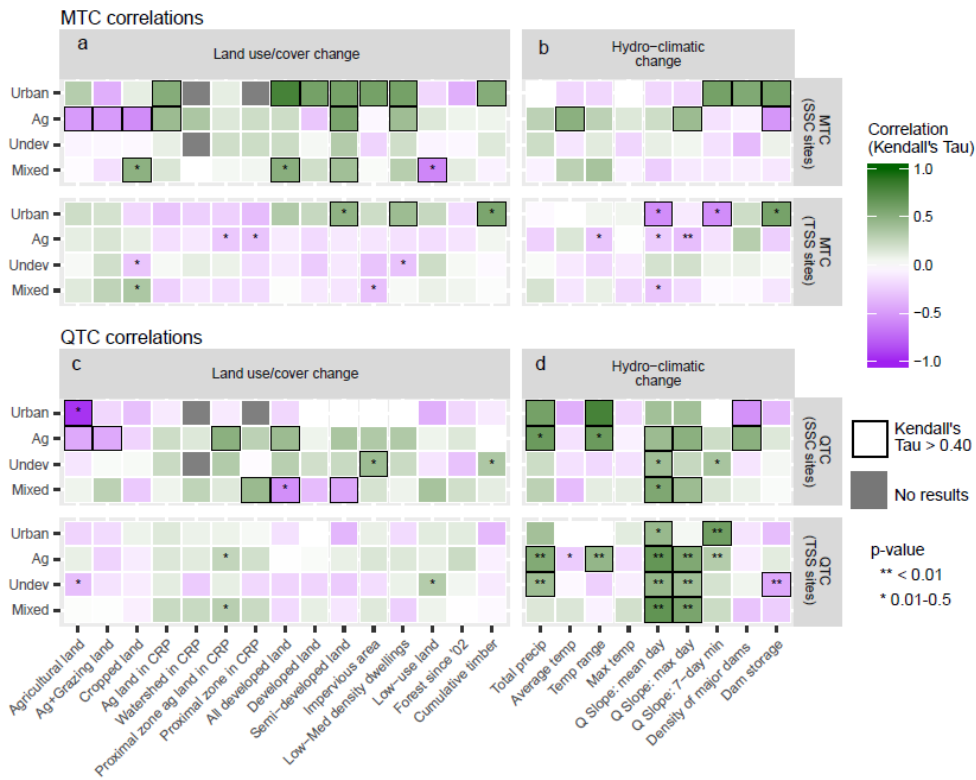
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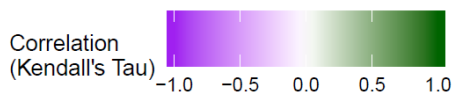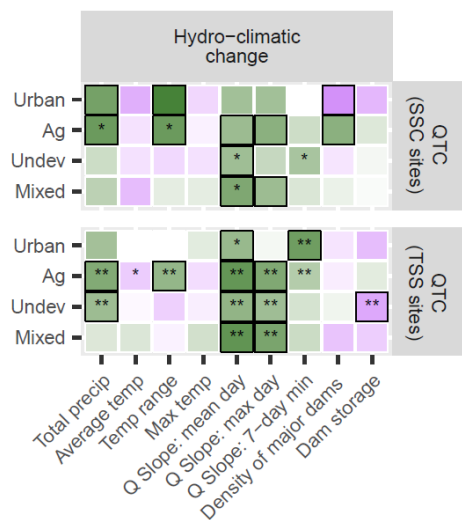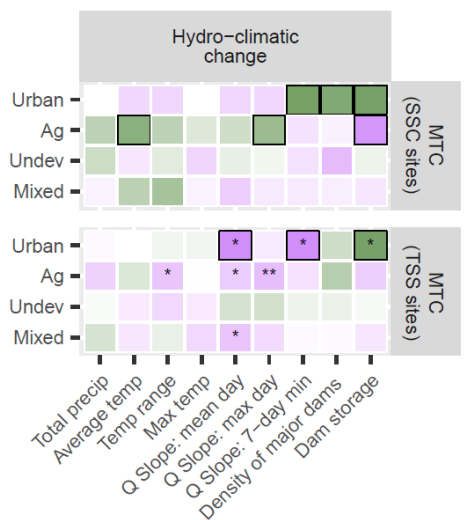
Figure 87. Correlations between (a) MTC or (b) QTC and watershed land -use/cover change andor hydro-climatic change variables and MTC or QTC, by sediment parameter. Sites grouped by 2012 land use of contributing watershed.