Section 1. Point-by-Point Replies to Referee Comments

Page and line numbers in point-by-point replies refer to the version of the paper published on 15 Mar 2017 unless otherwise stated, such as those in the margin comments. 15 Mar 2017 paper version available at: https://doi.org/10.5194/hess-2017-133

Section 1.a - Author Response to Referee #1: Ben Livneh (previous version published in HESS online discussion 28 April 2017: doi:10.5194/hess-2017-133-AC1, 2017)

First we would like to thank referee Ben Livneh for reviewing our manuscript and providing constructive feedback. Original comments by the referee are denoted by "Referee Comment" and our responses are denoted by "Author Response".

Referee Comment: Overview The authors address the interesting problem of disentangling anthropogenic versus climate impacts on hydrology in agricultural catchments in the mid-western US. They propose that storage has decreased dramatically in drained (tile) watersheds and discuss other aspects of the water budget, as well as conduct a break-point analysis to understand drivers of LCLUC changes. Overall, this is a wonderful analysis and the most interesting paper I've read in a while, so I'd like to commend the authors on a clearly articulated and thoughtful manuscript. A few points need to be clarified. However, I find the manuscript to be suitable for publication after minor revisions.

Author Response: Thank you! We are thrilled to hear that you find our analysis interesting and well-articulated.

Referee Comment: Major points INTRO, P2 second paragraph: do the widely reported systematic increases in peak, mean, total, and base flows from the literature attribute these to decreases in ET, or solely from increases in precipitation? This point needs to be clarified and discussed further.

Comment [SK1]: See changes made in this document on page 20

Author Response: Increases in streamflows reported on page 2, lines 8-12, have been attributed to the combined effects of increasing precipitation and decreased ET from land use changes, including agricultural tile drainage and replacement of perennial vegetation and/or hay and small grains to corn and soybean rotations.

For example, Frans et al. 2013 examined the relative contributions of increasing precipitation and land use land cover change to observed streamflows in the Upper Mississippi River Basin (UMRB), upstream of Grafton, IL. They show that ET is expected to increase with twentieth century agricultural expansion, except in the places they modeled agricultural tile drainage. When tile drainage is present, ET decreases, while total runoff increases. This is entirely consistent with what we propose in our manuscript. Necessarily, storage must decrease between the pre and post period in the agricultural river basins to explain modern day water budgets and streamflow patterns. Tile drainage can accomplish this decrease in storage by draining soil moisture that would have otherwise gone as ET or contribute to regional groundwater. Therefore, twentieth century tile drainage expansion is expected to decrease ET and increase total runoff.

Schottler et al. 2014 corroborated this finding, and developed an empirical relationship between water yield and amount of precipitation (P) that goes as potential evapotranspiration (PET), PET/P. Their findings suggest that the PET/P ratio has decreased during the twentieth century due to combined effects of climate and crop conversions, and has contributed to the observed increases in annual water yields.

We discuss changes in annual runoff ratios, precipitation, and evapotranspiration in section 4.2.1 (specifically p. 17, lines 7-14), and have included ET findings of other streamflow change studies further in the introduction of the revised manuscript, as recommended by the reviewer.

Referee Comment: P3L20: studies report reductions in early season ETâËŸAËGTpre- ˘ sumably these are because replacing mature grasslands with fledgling crops reduces ET early in the season. However, what occurs later in the season, when the crops matureâËŸAËGTwill the ET be greater than grasslands? ˘

Comment [SK2]: See changes made in this document on page 20

Author Response: Although studies generally agree that conversion of mature prairie or grasslands with annual row crops reduce ET early in the growing season, there are mixed findings about how this land cover conversion affects ET later in the growing season, as well as annually (p. 2, lines 16-19). Crop growth and water use (ET) are highly dependent on local antecedent conditions such as precipitation, wind, humidity, solar radiation, and crop growth stage. For example, Zeri et al. (2013) found that maize had the highest values of ET annually in 2009 but the lowest values of ET in the drought year 2011, when compared to water use by miscanthus, switchgrass, and native prairie in central Illinois. In general, total annual water use between annual row crops and native prairie are not drastically different in Iowa (Wolf and Market 2007). However the distribution of water use throughout the season may be differ depending on antecedent climate conditions, as well as crop planting, emergence, and harvesting date. Because row crops have a relatively short growing season – planted generally in late April through early June, maximum growth and water use generally occurring in July-August , and harvested in September-October – evapotranspiration rates can be greater than native prairie during the peak growing season (July/August) and less than native prairie during early spring and late fall (Wolf and Market 2007). We have clarified this point in our revised manuscript.

Referee Comment: What is the spatial resolution of the census drainage data? For which 5 years are drainage data available at the county-level?

Comment [SK3]: No change to manuscript.

Author Response: The census drainage data are reported at the county level for 1940, 1950, 1960, 1978, and 2012 (page 6, lines 14-16). These are, unfortunately, the best available data for this spatial extent.

Referee Comment: The use of the Livneh et al. hydrometeorology data allows for calculation of the water balance at scales that are appropriate for the analysis. Although the authors acknowledge that the derived hydrologic outputs, e.g. ET, were generated using a modeling framework that considered static vegetation cover, they should report (if possible), which vegetation cover was used in VIC, e.g. was it natural vegetation or crop land cover? This would bolster the authors acknowledgement of the limitation.

Comment [SK4]: See changes made in this document on page 26 and pages 62 & 63

Author Response: In a previously submitted version of the paper (doi:10.5194/hess- 2016-571, p. 28, lines 7-13) we discussed the limitations associated with using the Hansen et al. (2000) static global vegetation classification in the VIC model. Several referees suggested significant shortening of the manuscript. Upon our own review, we eliminated details (~2600 words) that were not essential to the manuscript. However, we agree that this would be a useful piece of information to convey for readers interested in this level of detail, so we will include this information in the Supplement of the revised manuscript.

Referee Comment: Would the use of static land cover of Livneh et al. (2013) mean that the authors results are a conservative estimate of LCLUC impacts, or would this mean that the authors findings would overestimate impacts?

Comment [SK5]: See changes made in this document on page 26 and pages 62 & 63

Author Response: As stated above, we originally discussed potential limitations of using the Livneh et al. (2013) evapotranspiration data in a previously submitted version of the paper and have included such discussions in the Supplement of the revised manuscript, specifically in discussion of Figures S4 and S5. In general, static vegetation that does not include tile drainage should mean the Livneh et al. (2013) ET estimates are overestimated in croplands, especially during modern times. This is exactly what we found when we compared the ET estimates to nearby Ameriflux stations in cropland cover (Figure S5). This potential bias is what allows us, independent of the climate drivers of ET change, to test whether drainage affects water balances. We anticipate that incorporating dynamic vegetation and tile drainage expansion in the VIC model would have reduced ET estimates and allowed for water budget closure in our analysis (i.e. storage term = zero). That said, Frans et al. (2013) tested the effects of dynamic vs. static cropland cover and found no statistically significant results of this effect on modeled annual runoff. Given that ET estimates between cropland and prairie are relatively similar, especially at annual scales, we do not think that dynamic land cover alone would have fully explained our water budget storage deficits, unless tile drainage was explicitly included.

Referee Comment: It would be useful to see a figure that shows historical land-cover change, precipitation change, and streamflow through time, if it is straightforward to show these together, as this would be very informative.

Comment [SK6]: No change to manuscript.

Author Response: While we appreciate this suggestion and have considered creating such a figure, the paper already contains ten figures, and we believe that incorporating the three suggested metrics into a single figure may become too cluttered for interpretation. We gladly welcome further suggestions from the referee as to how we might create such a figure, but our opinion is that the information is most effectively shown as three separate plots.

Referee Comment: Would it be possible to test the interpretation hypothesis (2) in the discussion, that precipitation intensity may be influencing runoff efficiency? This could be something for future work, but would be an interesting experiment.

Comment [SK7]: No change to manuscript.

Author Response: We agree that this would be a wonderful line of inquiry for future work, however this type of analysis should be written as a separate paper.

Referee Comment: Minor points I don't think "Midwestern" is a technical term, rather the Northeaster Great Plains is probably more apt and the authors should consider revising the references and title accordingly.

Comment [SK8]: No change to manuscript.

Author Response: While Midwestern may not be a formal ecoregion or physiographic province, the term is commonly used in academic literature to describe the large part of the US that is covered in our analysis. We believe it more effectively conveys the location to our audience than would the term Northeaster Great Plains.

Referee Comment: How did the authors reach the number of 286 for the t-test and KS-tests? This needs to be clarified as it is presently unclear.

Comment [SK9]: See changes made in this document on page 28

Author Response: Good catch. Thank you for the careful eye! We regret the error made on page 9, line 25, which should read "312 t-tests and 312 KS-tests...for a total of 652 statistical tests". On page 9, lines 16-17, we state that we ran all statistical tests using three defined breakpoints for each basin: three breakpoints X four study basins X 13 (or 12 monthly values + 1 annual value) = 156 t-tests and 156 KS-tests for each precipitation (P) and streamflow (Q) record, which is how we arrived at 312 t-tests and 312-KS-tests. Finally, 312+312+28 = 652 statistical tests total. This point will be clarified in the revised manuscript.

Referee Comment: All figuresâĔŸAĔG Tit is unacceptable to include acronyms in the ˘ figure and then not define them in the caption. The figures should be readable as standalones. Hence, the authors need to define all acronyms in each figure in the respective captions.

Comment [SK10]: See tables, figures, and caption text changes in this document, below

Author Response: We would like to thank the referee for the suggested comment and will define acronyms in individual figure captions.

Referee Comment: Figure 5, explain briefly how the flow was normalized in the caption.

Comment [SK11]: See figure 5 caption, p. 37

Author Response: We would like to thank the referee for the suggested comment and will define "Normalized Flow" in the figure caption.

References

Frans, C., Istanbulluoglu, E., Mishra, V., Munoz-Arriola, F. and Lettenmaier, D. P.: Are climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi River Basin?, Geophys. Res. Lett., 40(6), 1104–1110, doi:10.1002/grl.50262, 2013.

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Wolf, R.A., and Market, P.S.: On the impact of corn and soybeans to the local moisture budget in Iowa, National Weather Digest, 31(1), 3-7, 2007.

Zeri, M., Hussain, M. Z., Anderson-Teixeira, K. J., Delucia, E. and Bernacchi, C. J.: Water use efficiency of perennial and annual bioenergy crops in central Illinois, J. Geophys. Res. Biogeosciences, 118(2), 581–589, doi:10.1002/jgrg.20052, 2013.

<u>Section 1.b</u> - Author Response to Anonymous Referee #2

First we would like to thank Anonymous Referee #2 for reviewing our manuscript. Original comments by the referee are denoted by "Referee Comment" and our responses are denoted by "Author Response".

Referee Comment: This paper analyses observed changes in streamflow patters in four large basins of the Midwestern Unites States, and investigate their association with changes in climate (precipitation and evapotranspiration) and changes in land-use and land-cover, specifically the increasing cultivation of soybean and corn enhanced by artificial drainage. By analysing 79 years (1935 - 2013) of precipitation, streamflow, artificial drainage, and cultivation data, the authors provide a comprehensive statistical time series analysis to identify breakpoint years that could show relations between changes in magnitude and trends of the variables. Also, through the application of a simple water budget, the changes in basin storage are associated to changes in climate or in land-cover affecting streamflow response. The study concludes that artificial drainage as part of large agricultural development in the Midwestern US amplifies the changes in rainfall-runoff response because of an increased hydrologic connectivity and a reduced storage in the basin.

The paper is interesting, and the analysis is extensive and well structured, so it should be suitable por publication after revisions. Although the authors have reported a reduction in word count with respect to a previous version, some parts of the document could be paraphrased and made more concise. Overall, the methods applied are robust and the results are well described and presented. However, there are two issues that, I think, need to be attended by the authors, which are the reasons for recommending revisions and re-review:

Author Response: Thank you for finding our paper interesting and suitable for publication after revision. The suggested revisions are very much appreciated.

Major comments:

Referee Comment: The results section is an extensive description of the figures and tables, but less of an actual discussion and analysis. For example, the authors present all the numbers for each individual catchment repeatedly, but they don't compare these results with similar studies or discuss them in a broader context for interpretation. As this section is the main and longest part of the paper, after such a comprehensive exposition of results, the reader may feel disappointed not to find an equivalent discussion and interpretation of results. I would suggest to divide the section between Results (from a purely descriptive perspective only) and Discussion and Interpretation (extending on the current last section) to highlight better the value of this study and the findings. The closing Conclusions section could be short and concise as well.

Comment [SK12]: See changes made to manuscript in sections 4.1, 4.2.1, and 5 of the revised manuscript

Author Response: We appreciate the stylistic suggestion to separate the results and discussion sections. We have considered making this change, however, we present six distinct sets of analyses, each addressing specific questions. Therefore we believe the text is easier for the reader to follow if the results and discussion are presented together within each section. We do compare individual results to findings from other studies, e.g. p. 15, lines 14-16; p. 16, lines 28-31; p. 17, lines 10-12. We have removed a few sentences from the conclusion section, but in general believe that it provides a concise synthesis of our findings, a concise explanation of alternate hypotheses that can be pursued by future work, and a brief statement regarding the implications for policy and management.

Referee Comment: The study uses 7 metrics to analyse the streamflow regime, but it is not clear how and why these indices were selected. The literature is quite extensive with respect to hydrological indices to characterise and analyse streamflow features and alterations. See for example: Olden and Poff (2003); and Ochoa-Tocachi et al. (2016) for a list of indices used extensively in hydrological studies. The metrics (indices) depend on the streamflow attributes that the study is investigating, and ideally able to represent different parts of the hydrological response (independent, non-redundant) to provide more holistic views. The paper mostly focuses on streamflow magnitude, but there are other attributes (frequency, duration, timing, and flashiness) of flows that could be of interest. Lastly, it is not clear how the several streamflow gauges were used or, at least, the value of using several gauges in contrast to the downstream outlet only is lost.

Comment [SK13]: No changes made to manuscript

Author Response: We appreciate your suggestion and we are aware that many metrics can be used to quantify hydrologic change. The seven streamflow metrics presented in Figure 5 are consistent with those used in previous studies of Midwestern agricultural basins, and capture properties of streamflow typically used for management and decision making (e.g., Novotny and Stefan, 2007; Vandegrift and Stefan, 2010). However, we go well beyond these seven streamflow metrics and present numerous analyses of precipitation and streamflow change at the monthly timescale (Figures 6-8) as well as daily timescale (Figure 9). Other magnitude-frequency metrics have been used in our previous study (Foufoula-Georgiou et al., 2015), such as probability density function (pdf) of the slopes of the rising and falling limbs of the hydrographs, metrics of non-linearity, multi-scale energy decomposition via wavelets, and joint pdf of precipitation and next-day streamflow, etc., but they are beyond the scope of the present study. Data presented in Figure 5 include data from numerous gages within each of the basins, as specified in the caption. However, all other analyses were conducted for the gages at the mouths of the major watersheds, as stated in section 3.3.

Specific comments:

Referee Comment: P1L27: See other attributes of streamflow: magnitude, frequency, duration, timing, flashiness.

Comment [SK14]: See changes made to manuscript in this document, p. 20

Author Response: We have revised the statement to read "The magnitude, frequency, duration and timing of streamflows strongly influence water quality, sediment and nutrient transport, channel morphology, and habitat conditions of a river channel."

Referee Comment: P2L8-12: This is an example of a long sentence that could be divided or reduced.

Comment [SK15]: See changes made to manuscript in this document, p. 20

Author Response: Thank you for the suggestion. We split the sentence in two.

Referee Comment: P2L15: Specify if the term runoff refers to overland flow or total streamflow.

Comment [SK16]: No change made to manuscript

Author Response: P2L15: We use the word runoff on page 2, line 15 to make a general statement acknowledging recent hydrologic changes in the Midwest. If we were referring to overland flow, we would have used that term. We believe that the use of the word runoff is appropriate as written.

Referee Comment: P2L21: Try not to cite articles not published yet.

Comment [SK17]: No change made to manuscript

Author Response: Thank you for this comment. We included this as a placeholder, anticipating that the Lauer et al., paper will be published before the HESS paper, which we still expect to be the case.

Referee Comment: P3L6: Although the term "artificial drainage" is used several times in the first subsection, it is only defined at this point. Maybe you could move the definition to the first time the term is mentioned.

Comment [SK18]: No change made to manuscript

Author Response: Thanks for the suggestion. We considered moving the definition earlier in the paper. However, the statements made in the previous section are all very high level points and inserting a specific definition negatively impacts the flow. Section 1.2 is focused on explaining the details of artificial drainage, so we believe it is the best place to provide this explanation.

Referee Comment: P3L18: As part of another long sentence, it is unclear if the phrase between the commas ", at least for well drained soils (Hamilton et al., 2015)," refers to a study that does not show a reduction in ET, or if this is a condition for the following studies that report such reduction.

Comment [SK19]: See changes made to manuscript in this document, p. 22

Author Response: The phrase between the commas is meant to refer to the former statement. We have clarified this in the revised manuscript by splitting the sentence in two.

Referee Comment: P5L3: The acronym PRISM is used here, but only introduced in the next section. Try to define acronyms the first time they are mentioned.

Comment [SK20]: See changes made to manuscript in this document, p. 23

Author Response: Thank you for pointing this out. We deleted the term PRISM in this case as the important point is that we are talking about annual long term means. We cite the source of the data (and explain the acronym PRISM) in the figure caption as cited. PRISM is also explained now in its first usage in the text, at the beginning of section 3.2.

Referee Comment: P5L21: When referring to tile installation, clarify that it is the "ANNUAL installation (or installation RATE) [which] has increased from 3 miles in 1999 to 1,924 miles in 2015".

Comment [SK21]: See changes made to manuscript in this document, p. 24

Author Response: Thank you for this suggestion. We clarified that it is the annual installation that has increased. Additionally, we have converted the lengths to SI units. We initially used imperial units because those were the measurement units reported in the cited report. However, SI units are more appropriate for our global audience.

Referee Comment: P6L4: Generally the acronym for land-use and land-cover changes is (LUCC). However, as this term is widely used across the paper, check what is the most common term in the literature for your potential readers, if you want to keep LULC change as it is.

Comment [SK22]: No change made to manuscript

Author Response: Thank you for the suggestion. However, we would prefer to keep the acronym LULC, also used in our previous work and many other papers in the literature. Also, we prefer not to incorporate “change” in the acronym. For example, we talk about LULC of a basin during different periods of time, and then infer “change” by comparison.

Referee Comment: P9L11: As the authors mention, when fo»0, the Morlet wavelet is simplified. Is the value of fo=0.849 considered much greater than 0?

Comment [SK23]: No change made to manuscript

Author Response: Yes, for any value of f0>0.8 the second term inside the parenthesis of equation (2), which corrects for the non-zero mean of the wavelet, becomes negligible, making (3) a proper wavelet of zero mean. The selection of the specific value of f0=0.849 (=1/sqrt(1/(2ln2)) is commonly used in practice as it produces a decay where the magnitude of the two peaks in the real waveform adjacent to the central peak are half its amplitude (see Addison, 2017, and also Appendix A in Foufoula-Georgiou et al., 2015).

Referee Comment: P18L3-8 and P18L27-P19L2: These two groups of sentences should not be part of the results but of the methods as they explain how the figures must be read. This is an example of how the results section could be shortened.

Comment [SK24]: No change made to manuscript

Author Response: We respectfully disagree with the referee’s suggestion that these statements should be move to the methods. Indeed, these statements help the reader understand what is being presented in the figures and how to read them. Therefore, we feel strongly that they are most appropriate and useful to the reader in the results section. We are not presenting new methods here, just reminding the reader of what these data represent.

Referee Comment: P21L3: Flashiness (and flashy) is actually an attribute of streamflow, so no quotation marks are needed. The term "rate of change" of flows can also be used. Check the comment on the selection of metrics.

Comment [SK25]: See changes made to manuscript in this document, p. 41

Author Response: Thank you for your suggestion. We have removed the quotation marks around the word flashiness here and elsewhere throughout the paper.

References

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<u>Section 1.c</u> - Author Response to Anonymous Referee #3

First we would like to thank Anonymous Referee #3 for reviewing our manuscript and providing constructive feedback. Original comments by the referee are denoted by "Referee Comment" and our responses are denoted by "Author Response".

Referee Comment: The authors use a variety of methods to characterize the changes in hydrology in four large Upper Midwest USA watersheds due to precipitation and land cover change. The focus of the work is relevant to the region and deserving of publication. The paper is well-written but several points are worthy of additional attention:

Author Response: Thank you for your review of the paper, and for considering our work well written and relevant.

Referee Comment: 1. Page 2, Lines 15-30- The authors insist that the main issue associated with increased flows and base-flows is increasing sediment loads. This is an issue very close to their working group in Minnesota. However, for the rest of the Midwest, the issue is increasing nutrient loads, specifically nitrate and phosphorus. Tile drainage is the main source of nitrate to rivers and it is barely mentioned in the paper. Outside of the Minnesota River, tile drainage is rarely mentioned along with bank erosion but the issue of tile drainage is universally considered a dominating factor in nitrate and dissolved phosphorus transport. The authors should change their focus to include more discussion of the relevance of increasing flows on nutrient export and Gulf Hypoxia. There is a wealth of papers on this topic that can be considered and they are largely ignored in the paper.

Comment [SK26]: See changes made to manuscript in this document, p. 20,21,45

Author Response: Thank you for pointing out this oversight. We agree that additional discussion of linkages to other water quality problems will greatly enhance the impact of the paper. We are aware of the vast literature on the topic (e.g. David et al., 1997; Goolsby et al., 1999; Kreiling and Houser, 2016; Letey et al., 1977; Randall and Mulla, 2001; Royer et al., 2006; Schilling et al., 2017; Sims et al., 1998 to name a few). We focused on sediment in part because it is the primary focus of our research group, as the reviewer points out, but also because there is so much known/written about the linkages between artificial drainage and nutrients and we believe it is important to highlight other indirect effects of tile drainage, such as increased bank erosion and thus fine sediment loads, which also degrade water quality in the US and globally. Understanding the many effects of tile drainage in agricultural landscapes underscores the continued need for better drainage management practices. Nutrients were already briefly mentioned in the abstract, introduction and conclusion. We have better clarified our attention to sediment and incorporated additional discussion of broader water quality concerns in the introduction and conclusion of the revised manuscript.

Referee Comment: 2.Likewise the authors ignore research conducted on this issue previously including: Xu, Xianli, et al. "Relative importance of climate and land surface changes on hydrologic changes in the US Midwest since the 1930s: Implications for biofuel production." Journal of Hydrology 497 (2013): 110-120. This paper used some different methods to derive some assessment of the topic. There are other papers where this came from. The topic is not new and the authors should compare their results to the body of literature reporting on the same topic.

Comment [SK27]: See changes made to manuscript in this document, p. 20,22,35,37,43

Author Response: We are familiar with the work of Xu et al. 2013 and cited their work in previous versions of the paper. While revising and shortening the paper, we must have deleted statements citing their work. We apologize for this oversight.

We agree that the work by Xu et al. 2013 and others have contributed to the vast body of literature on the topic. We discuss how our findings compare to work by other authors on the topic – p. 15, lines 14-16; p. 16, lines 28-31; p. 17, lines 10-12. We have re-added the citation to Xu et al., 2013 and have bolstered our discussion of how our work compares to Xu et al. 2013 and other studies in the revised manuscript.

Referee Comment: 3. Page 5, lines 7-23 - The authors again ignore a body of research on the extent of tile drainage in the US Midwest (search for papers from Mark David in JEQ). There are much better estimates of tile drainage extent available than NASS. What is the source of the percentages in line 19?

Comment [SK28]: See changes made to manuscript in this document, p. 26

Author Response: We respectfully disagree with the referee's claim that "there are much better estimates of tile drainage extent available than NASS". In some states, estimates of tile drainage extent, taken from different sources, vary by a factor of two (Sugg, 2007). David et al. 2010, acknowledge that estimates of tile drainage extent can be made using a variety of GIS and aerial imagery approaches; however these methods are only feasible over small spatial extents, and usually have limited temporal resolution. Therefore, David et al. 2010 rely on county level, best guess estimates from Sugg (2007). We discuss the limitations of the Sugg (2007) approach to making tile drainage estimates in the revised manuscript. However, we stand by our decision to report land use changes in each basin by reporting county-level drainage data from five US Census of Agriculture reports, as well as annual NASS crop cover data.

The source for the percentages in line 19 come from the USDA National Agricultural Statistics Service Cropland Data Layer. {2013}. Published crop-specific data layer [Online]. Available at https://nassgeodata.gmu.edu/CropScape/ (accessed {1 Oct 2016}; verified {19 May 2017}). USDA-NASS, Washington, DC. We have clarified and cited this source in the Figure 1 caption of our revised manuscript.

Referee Comment: 4. Page 5 line 3 - PRISM used without definition; Page 7 lines 13 and 27 it is defined twice.

Comment [SK29]: See page 26, line 12 in this document

Author Response: Thank you for your attention to detail! We have deleted PRISM from p. 5 ,line 3 as it is unnecessary to introduce here. Therefore, in the revised manuscript (see below in this document) PRISM is defined the first time it is mentioned, on p. 26, line 12.

Referee Comment: 5. Page 8 CWT methods - there is a lot of method text devoted to this method but it did not prove add much to the results and discussion. In fact it is largely ignored later in the paper in a single short paragraph. I would suggest dropping this method or simply mentioning that it was done and moving to supplemental text. It adds nothing to your argument.

Comment [SK30]: See changes made to manuscript in this document, p. 28

Author Response: The referee is correct that we devote 18 lines to the CWT methods in section 3.4. We have shortened the text in this section of the revised manuscript, and removed one equation from the text.

Referee Comment: 6. Page 9, line 12-19 - the rationale for the breakpoint based on plastic pipe is purely speculative and it gives this idea credence. Just simply break the record up in two equal periods consistent with previous work.

Comment [SK31]: No change made to manuscript

Author Response: : We have used the term 'roughly' to indicate that while the date of widespread acceptance of corrugated plastic tile is not exactly know, the timing of our breakpoint is consistent with what is generally thought to be the transition, as documented by Fouss and Reeve, 1987.

Referee Comment: 7. Where did the ET data for crops come from? The water balance method is hugely sensitive to ET and it seems rather arbitrary to reduce it by 17% because of a literature citation. This needs to be verified independently by the authors. Maybe its 25% or 10%, who knows, and yet it is retained in the results and discussion like there is true meaning behind it.

Comment [SK32]: No change made to manuscript

Author Response: We used ET data from Livneh et al. 2013 (L13) for water balance calculations (p. 7, lines 18-24). We have, in fact, compared independent ET estimates from L13 to other sources in the Supplement (Figs. S4 & S5) and describe our rationale for applying the 17% reduction in JJA (page 10, lines 24-39). This adjustment does not change the interpretations of the water budget; it simply represents our effort to err on the conservative side with the water budget (p. 23, lines 5-7). Livneh also reviewed our manuscript and did not object to this correction we applied. In any case, eliminating the 17% reduction would only strengthen the conclusion we reach, but we feel it is more reasonable to err on the conservative side with this calculation.

Referee Comment: 8. Section 4.1 - this seems like background material to me. You didn't really do anything new here except compile some data available in databases. Again, the NASS data is pretty weak for these trends, especially trends reported as if they are completely accurate. This is qualitative data at best.

Comment [SK33]: See changes made to manuscript in this document, p. 30-31

Author Response: The referee is correct that in section 4.1 we present information compiled from data available in databases. This section represents a tremendous effort that mainly yielded qualitative interpretations. However, we believe that this section is sufficiently important to include in the paper as it further highlights the poor documentation and availability of drainage data in the United States, a point we wish to emphasize as we believe it has important policy implications. These data need to be better collected and archived so that researchers, policymakers and managers can easily access this information instead of gleaning information from scanned copies of mid-20th century census reports. Presenting the incomplete, yet best available information regarding histories of drainage and cropping practices in our four study basins bolsters our conclusion that the most parsimonious explanation for reductions in watershed storage are caused by drainage practices for corn-soy agriculture (p. 23, lines 7-9). In any case, we have shortened this section to the extent possible, without eliminating any of the key points.

Referee Comment: 9.Page 6, lines 16-21 - it is a stretch to cite Figure 5 to discuss cyclicity. It is not obvious in the figure. suggest that the authors find a way to make it visible or drop from the text.

Comment [SK34]: No change made to manuscript

Author Response: Having shown and discussed this figure with many people over the past few years, none have questioned the cyclicity that emerges over the past ~35 years in the MRB with a 10-12 year wavelength. Granted, there are only 3 cycles, but the pattern seems sufficiently clear to at least mention. We agree with the reviewer that this observation does not substantially impact our results or interpretations substantially, but believe it is worth pointing out for future research.

Referee Comment: 10. I found the data is Figure 6 to be the most compelling in the paper. Are the deviations consistent with the imposed breakpoints?

Comment [SK35]: No change made to manuscript

Author Response: The deviations between P and Q coincided well with the breakpoints identified from the CWT and reported in Table 3. Regardless, the results of all statistical tests are not sensitive to breakpoints spanning four decades (p. 9, lines 26-26; Supplement Table S1)

Referee Comment: 11. Section 4.2.3 - the use of daily scale in this multi-year analysis is inappropriate. The results are very weak and do not really add to your argument. What about the "flashiness index"? There is no real link of this section to your main issues and I would suggest dropping this section.

Comment [SK36]: See changes made in this document, p. 41

Author Response: We briefly discuss daily streamflow metrics in this multi-year analysis to demonstrate that streamflows are changing across multiple scales. We believe this point is sufficiently important to include as we expect that the broader water sciences community (namely aquatic ecologists and geomorphologists) are interested in streamflow changes at sub-annual and sub-seasonal scales. Flow flashiness is important for aquatic organisms, nutrients, sediment transport and river channel change. The changes we document, especially for the May-June time period, are large. We are further investigating these daily-scale changes in other ongoing research. Nevertheless, in response to the reviewer's concern we will reduce the content of this section and better link these results to the main questions and key points in the revised manuscript.

Referee Comment: Overall, the paper adds to the body of research that already exists on the topic. The topic is not new and it has been evaluated by many authors previously but there are some methods and techniques used and the issue of worthy of attention. I am recommending the paper be accepted with major revisions.

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<u>Section 1.d</u> - Author Response to Anonymous Referee #4

First we would like to thank Anonymous Referee #4 for reviewing our manuscript. We are happy to incorporate specific changes in the revised manuscript based on the referee's suggestions, and would benefit from further clarification of general comments made by the referee. Original comments by the referee are denoted by "Referee Comment" and our responses are denoted by "Author Response".

Referee Comment: This paper treats an interesting topic: the effect of human activities on the precipitation-runoff patters in the Midwestern United States. In the last century, the land transformation from natural to agriculture and urban areas seriously affected changes in the hydrology of the study area. The results suggested that storage has decreased in intensively drained and cultivated basins by 30%-200% since 1975, but increased by 30% in the less agricultural basin. This has amplified the streamflow response to precipitation increases in the Midwest. While the results are quite interesting some important information is obscured or not well described:

Author Response: It is difficult for us to provide a thorough reply without more information from the reviewer regarding the relevance of each of these items to our analysis and interpretations. References to page/line numbers would have also been helpful.

Referee Comment: - infiltration and hydraulic soil properties (e.g. spatial data)

Comment [SK37]: See changes to text on pa
23 in this document in response to AR#4's comm

Author Response: We included descriptions of the soils in each of the watersheds in a previous version of this paper (reviewed in HESS), but found that it did not substantially contribute to the analysis and interpretations. Our study evaluates precipitation-runoff patterns at very large scales. Soil types vary considerably within our watersheds, which largely precludes any meaningful quantitative analysis of if/how soil properties themselves influence the hydrologic patterns we observe. However, in response to the reviewer's concern we will briefly describe soils in each of the watersheds in Section 2 in the revised manuscript and include the following statements:

"Soils in the Minnesota River Basin consists of organic rich, but poorly drained mollisols with a very small area consisting of alfisols and entisols (Stark et al., 1996). The Illinois River basin is generally dominated mollisols, containing around 1% organic matter and generally of low to very low permeability, with some presence of more permeable alfisols and entisols (Arnold et al., 1999; Groschen et al., 2000). The dominant soil orders found in the Red River of the North basin include mollisols and alfisols with some areas underlain by entisols and histosols (Stoner et al., 1993). In the Chippewa River basin, alfisols and spodosols are most prevelant, with occasional pockets of entisols, mollisols, and histosols (Hartemink et al., 2012; Soil Survey Staff, NRCS)."

Regarding infiltration, no quantitative measurements exist. Models of infiltration are inadequate to produce reliable information at these very large scales. For that reason we have not discussed infiltration in our study.

Referee Comment: - water storage capacity of ditches (what kind of ditches are these? Only surface drainage system? What about the sub-surface drainage network?)

Comment [SK38]: No change to manuscript

Author Response: In this paper, we provide all available information on surface and sub-surface drainage. In several locations throughout the manuscript we discuss the fact that very little quantitative information is available for the sub-surface network. We do, however, report county-level drainage data from five US Census of Agriculture reports. These reports include both surface and subsurface drainage, but exclude private lands less than 500 acres; these data likely underestimate actual drainage extent considerably, as the majority of farms in Minnesota, Illinois, North Dakota, and Wisconsin are less than 500 acres (p. 6, line 16; p. 11, lines 21-23). Qualitatively we don't have any reason to believe that the surface water storage capacity of ditches in these watersheds has changed substantially.

Referee Comment: - methodology to recognize/map ditches (the authors highlighted some issues in the underestimation of their extent; is this issue critical for the suitability of the final results?)

Comment [SK39]: No change to manuscript

Author Response: We believe that inaccurate and incomplete public information on agricultural drainage systems is a critical issue that limits scientific and management understanding of how drainage influences streamflow regimes and nutrient transport across scales (especially in the Mississippi River Basin). We discuss this point several times in the paper. While we are cognizant of, and transparent about, these limitations, we have specifically chosen analyses that circumvent the need for such information to the extent possible (such as the water budget). So, as we discuss in the manuscript, we believe better constraints could be obtained on the impact of artificial drainage at large spatial scales if/when better information on drainage practices is available.

Referee Comment: - surface runoff related to the different agriculture practices through years.

Comment [SK40]: No change to manuscript

Author Response: Surface runoff is integrally linked to infiltration. As we stated above, no quantitative information is available to constrain this process.

Referee Comment: Also, some recent relevant papers related to the drainage ditch role in water storage capacity, effects of the changes in drainage ditches density and agricultural practices on water storage capacity are missed in the literature review.

Comment [SK41]: No change to manuscript

Author Response: There is an immense body of literature on agricultural tile drainage, and we have tried to review papers most relevant to our study. Further elaboration on tile drainage could detract from the main points of our paper (p. 3, lines 28-32). If there is a specific paper on the topic that the referee would like to see us reference, please let us know.

Referee Comment: Unfortunately, because of the above critical issues, the paper needs to be restructured adding extra info to provide a more clear view of the processes involved in the study area.

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Section 2. Revised Manuscript with Edits as Track Change

Page and line numbers refer to this document unless otherwise stated.

Human amplified changes in precipitation-runoff patterns in large river basins of the Midwestern United States

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Abstract. Complete transformations of land cover from prairie, wetlands, and hardwood forests to row crop agriculture and urban centers are thought to have caused profound changes in hydrology in the Upper Midwestern US since the 1800s. In this study, we investigate four large (23,000-69,000 km^2) Midwest river basins that span climate and land use gradients to understand how climate and agricultural drainage have influenced basin hydrology over the last 79 years. We use daily, monthly, and annual flow metrics to document streamflow changes and discuss those changes in the context of precipitation and land use changes. Since 1935, flow, precipitation, artificial drainage extent, and corn and soybean acreage have increased across the region. In extensively drained basins, we observe 2 to 4 fold increases in low flows and 1.5 to 3 fold increases in high and extreme flows. Using a water budget, we determined that the storage term has decreased in intensively drained and cultivated basins by 30%-200% since 1975, but increased by roughly 30% in the less agricultural basin. Storage has generally decreased during spring and summer months and increased during fall and winter months in all watersheds. Thus, the loss of storage and enhanced hydrologic connectivity and efficiency imparted by artificial agricultural drainage appear to have amplified the streamflow response to precipitation increases in the Midwest. Future increases in precipitation are likely to further intensify drainage practices and increase streamflows. Increased streamflow has implications for flood risk, channel adjustment, and sediment and nutrient transport and presents unique challenges for agriculture and water resource management in the Midwest. Better documentation of existing and future drain tile and ditch installation is needed to further understand the role of climate versus drainage across multiple spatial and temporal scales.

1 Introduction

1.1 Whether humans, climate or both have caused streamflow change matters for water quality and watershed management

The magnitude, ~~and~~ frequency, duration and timing of streamflows strongly influence water quality, sediment and nutrient transport, channel morphology, and habitat conditions of a river channel. While streamflows fluctuate naturally over event to millennial timescales, humans have also altered rainfall-runoff processes in pervasive and profound ways (Vörösmarty et al., 2004). For example, humans have substantially altered the timing and magnitude of evapotranspiration, have dammed, channelized and leveed waterways, and have installed artificial drainage networks in former wetlands (Boucher et al., 2004; Dumanski et al., 2015; Rockström et al., 2014; Schottler et al., 2014; Vörösmarty et al., 2004) . While it is inevitable that wetland removal and artificial drainage will change rainfall-runoff processes, the effects of drainage on the hydrologic cycle may be subtle and difficult to discern, and may manifest differently at different spatial scales and times of year (e.g., Bullock and Acreman, 2003; Foufoula-Georgiou et al., 2016; Irwin and Whiteley, 1983; O'Connell et al., 2007).

Systematic increases in peak, mean, total, and base flows are widely reported in the Midwestern USA. Such increases have been ~~and~~ attributed to changes in climate, such as increasing precipitation and earlier snowmelt, and land use, including widespread conversion from perennial vegetation, such as grasses, to annual row crops, primarily corn and soybean, and the addition of artificial drainage (e.g. Foufoula-Georgiou et al., 2015; Frans et al., 2013; Gerbert and Krug, 1996; Juckem et al., 2008; Novotny and Stefan, 2007; Schilling and Libra, 2003; Schottler et al., 2014; Xu et al., 2013; Zhang and Schilling, 2006). Furthermore large-scale, land use land cover (LULC) changes influence surface energy fluxes and thus have feedbacks on climate and water balances. As a result of the Green Revolution, net primary production increased during the 20th Century in the Midwestern US, which subsequently increased ET demands, especially during the peak growing season (Mueller et al., 2015). Corn yields (bushels per acre) tripled in the US between 1949 and 1989 (U.S. Department of Agriculture Bureau of Agricultural Economics Crop Reporting Board, 1949; U.S. Department of Agriculture National Agricultural Statistics Service Agricultural Statistics Board, 1990). However, any increase in ET demand due to crop yield increases may have been offset during this time by the addition and replacement of agricultural drainage. Regional studies have reported increases in Midwestern crop yields and yet simultaneously decreases in ET for artificially drained agricultural basins, where streamflows have subsequently increased during the 20th Century. (Frans et al., 2013; Schottler et al., 2014). ~~However~~Therefore, the question remains: how have combined climate and land use changes affected streamflows in very large (>10^4 km^2) watersheds, the scale at which many states and federal programs are often tasked with monitoring and evaluating water quality?

Many basins across the Midwestern ~~c~~Corn ~~b~~Belt and around the world are experiencing greater runoff, higher sediment and nutrient loads, and accelerated loss of habitat than in the past (Blann et al., 2009). Linkages between artificial

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Comment [SK45]: Text addresses major poin made by referee Livneh agricultural drainage and increased nutrient export have been well documented (David et al., 1997; Goolsby et al., 1999; Kreiling and Houser, 2016; Letey et al., 1977; Randall and Mulla, 2001; Royer et al., 2006; Schilling et al., 2017; Sims et al., 1998). Less research has focused on the implications of hydrologic change for sediment loads in agricultural landscapes. For waters impaired by sediment under the US Clean Water Act (CWA), EU Water Framework Directive, and similar regulations around the world, loads often consist of both natural and human-derived sediment sources (Belmont et al., 2011; Gran et al., 2011; Belmont and Foufoula-Georgiou, 2017). Differentiating between these two sources is often very difficult, and yet essential for identifying and achieving water quality standards (Belmont et al., 2014; Trimble and Crosson, 2000; Wilcock, 2009). Sediment sources derived from near or within the channel itself (e.g., bank erosion from channel widening) are particularly sensitive to changes in streamflows (Lauer et al., in review; Schottler et al., 2014; Lenhart et al., 2013). Bank erosion is a significant sediment source in many alluvial rivers, contributing as much as 80% to 96% of the sediment that comprise a river's total sediment load (Kronvang et al., 2013; Palmer et al., 2014; Schaffrath et al., 2015; Simon et al., 1996; Stout et al., 2014; Willett et al., 2012). For some agricultural basins, erosion of near-channel sources contributes more fine sediment than does agricultural field erosion (Belmont et al., 2011; Lenhart et al., 2012; Trimble, 1999). However, if artificial drainage practices act to amplify streamflows, then the source of accelerated bank erosion may still be linked to agriculture. Artificial drainage is currently unregulated at the federal level in the US and many countries around the world. Therefore, in stark contrast to urban hydrology, progress in understanding the effects of agricultural drainage has been hindered by the fact that accurate data regarding the location, size, depth, efficiency and connectivity of sub-surface drainage systems are rarely available.

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1.2 Artificial drainage improves agricultural productivity but may amplify streamflows in large watersheds

The United States is the largest producer of corn and soybeans in the world (Boyd and McNevin, 2015; Guanter et al., 2014). Exceptionally high agricultural productivity over the past century and a half required massive conversion of grasslands, wetlands, and forests to agricultural lands (Dahl, 1990; Dahl and Allord, 1996; Marschner, 1974). Although many advances in cropping practices have led to the modern day prosperity of the Corn Belt, artificial drainage has played a critical role for agriculture in the Midwestern USA. Throughout this paper "artificial drainage" is used as a general term that refers to both human installed surface ditches and subsurface tile drainage. Tile drains and ditch networks are installed to ameliorate water-logged soils, which are known to limit crop growth (Hillel, 1998; Sullivan et al., 2001; Wuebker et al., 2001). Modern tile drains are composed of corrugated plastic tubing and are typically installed at depths of 1-2 m to control the elevation of the water table below the soil surface (Hillel, 1998).

The economic benefits of artificial drainage are well understood by Midwestern farmers, who have invested heavily in drainage systems to reduce soil moisture, surface overland flow, and soil erosion, and increase land value, ease of equipment operation, and production of first class crops such as corn and soy (Burns, 1954; Fausey et al., 1987; Hewes and

Frandson, 1952; Johnston, 2013; McCorvie and Lant, 1993). Installation or enhancement of tile drainage systems often occurs simultaneously with land conversion from wild hay and small grains to soybeans, as Fig. S1 demonstrates in the Supplement (Blann et al., 2009; Burns, 1954; Hewes and Frandson, 1952). ~~Although the c~~Conversion of perennial grasses to corn and soybean rotations doesn't necessarily lead to a reduction in evapotranspiration (ET) over the course of an entire growing season, at least for well drained soils (Hamilton et al., 2015). However,~~,~~ several studies report a reduction of ET early in the growing season (Hickman et al., 2010; McIsaac et al., 2010; Schottler et al., 2014; Zeri et al., 2013) and greater evapotranspiration rates than native prairie during the peak growing season (Wolf and Market, 2007; Zeri et al., 2013). Thus changes in land cover (and ET) and drainage expansion have been found to alter watershed hydrology and increase mean annual flows (Harrigan et al., 2014; Kibria et al., 2016), base flows (Juckem et al., 2008; Robinson, 1990; Schilling and Libra, 2003; Xu et al., 2013), annual peak flows (Dumanski et al., 2015; Magner et al., 2004; Skaggs et al., 1980, 1994), and total flow volumes (Dumanski et al., 2015; Frans et al., 2013; Lenhart et al., 2011). While it seems inevitable that altering ET and subsurface drainage efficiency should have measureable effects on streamflow, the combined effects have proven difficult to isolate empirically, especially across scales, due to measurement uncertainties, high temporal and spatial variability in antecedent moisture conditions and runoff processes, a shift towards a wetter climate today than in the historical past, as well as limited documentation of artificial drainage installation in the US.

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In this paper we couple analysis of historical patterns in large (>10^4 km^2) river basin hydrology in the Midwestern USA with historical climate and land use data to identify how each of these factors have influenced streamflow patterns. Specifically, we address the following questions: (1) how have land use, climate, and streamflows changed during the 20th and 21st centuries; (2) what are the timing, time scales and times of year that changes are most prominent; and (3) can changes in climate alone explain changes in streamflow? We hypothesize that in the most intensively managed agricultural basins, climate alone cannot explain streamflow patterns, and that land use changes in the Midwestern USA have amplified the expected hydrologic change associated with climate. We test this hypothesis in four large river basins with different histories and climates using a suite of quantitative methods that test the statistical significance of changes in streamflow and precipitation at multiple time scales. Finally, we present a water budget for each basin.

We acknowledge that the conversion of precipitation to streamflow occurs by a complex suite of physical processes. Inevitably, we lack temporal and spatial coverage/resolution of all of the relevant hydrologic fluxes (e.g., groundwater, actual evapotranspiration, infiltration, soil water flux rates) to characterize the system completely and have limited ability to ascribe subtle changes to any given physical process, especially at large scales. Yet, with increasing concerns about water quality and aquatic biota, disentangling the effects of artificial drainage and changing precipitation patterns is important for evaluating economic costs, benefits and risks, predicting the effects of future land and water management and informing future policy.

2 Study areas: large river basins of the Midwest with varying degrees of climate and land use change

We analyze hydrologic and land use change in four large Midwestern watersheds during 1935-2013. We selected these basins for the following reasons: all are agricultural, to various degrees, primarily producing corn and soybeans; all are located mainly within the Central Lowland physiographic province and were affected by continental glaciation resulting in mostly flat, poorly drained uplands and incised river valleys (Arnold et al., 1999; Barnes, 1997; Belmont et al., 2011; Day et al., 2013; Gran et al., 2009; Groschen et al., 2000; Rosenberg et al., 2005; Stark et al., 1996); and all are characterized by a humid, temperate climate (Kottek et al., 2006). Additionally, all four basins also contain waters impaired for excessive sediment under the US Clean Water Act. Therefore, deconvolving climate and land use effects on basin hydrology is essential for developing and attaining sediment- and nutrient-related water quality standards. Despite the broad similarities between basins, we have intentionally selected watersheds that span a gradient of climate and land use change. From northwest to southeast, these include: the Red River of the North basin (RRB), upstream of Grand Forks, ND (67,005 km^2), Minnesota River basin (MRB), upstream of Jordan, MN (42,162 km^2), Chippewa River basin (CRB), upstream of Durand, WI (23,444 km^2), and Illinois River basin (IRB), upstream of Valley City, IL (69,268 km^2) (Fig. 1).

Soils in the Minnesota River basin consists of organic rich, but poorly drained mollisols with a very small area consisting of alfisols and entisols (Stark et al., 1996). The Illinois River basin is generally dominated mollisols, containing around 1% organic matter and generally of low to very low permeability, with some presence of more permeable alfisols and entisols (Arnold et al., 1999; Groschen et al., 2000). The dominant soil orders found in the Red River of the North basin include mollisols and alfisols with some areas underlain by entisols and histosols (Stoner et al., 1993). In the Chippewa River basin, alfisols and spodosols are most prevelant, with occasional pockets of entisols, mollisols, and histosols (Hartemink et al., 2012; Soil Survey Staff, NRCS).

There is a broad northwest to southeast precipitation and temperature gradient across the region (Fig. S2). The RRB is the coldest and driest of all four study basins, although the last two decades (1990's and 2000's) have been the wettest in historical times. Precipitation records, lake level elevations, and paleoclimate studies indicate that the basin is prone to extreme climate variability (Fritz et al., 2000; Miller and Frink, 1984). Much like the RRB, the adjacent MRB is uniquely situated at a "climatic triple junction" where warm moist air from the Gulf of Mexico, cold dry air from the Artic, and dry Pacific air dominate at different times of the year and have varied in relative dominance in the past (Dean and Schwalb, 2000; Fritz et al., 2000). Temperature and humidity in the CRB are more strongly influenced by the Great Lakes than in the other basins. The southwest IRB generally receives more precipitation than the northeast in all months. On average each basin from northwest to southeast receives 589 mm, 716 mm, 822 mm, and 960 mm annually, with 59%-68% of the annual precipitation falling in the spring (MAM) and summer (JJA) months based on ~~PRISM~~ annual long term means, 1981-2010 (Fig. S2). Recent increases in precipitation and streamflows have been reported across the region during the last few decades

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(Foufoula-Georgiou et al., 2015; Frans et al., 2013; Gerbert and Krug, 1996; Groisman et al., 2001; Juckem et al., 2008; Novotny and Stefan, 2007; Schottler et al., 2014).

Settlement, agricultural intensification, and development differ in timing and intensity among basins but are generally similar. During the early to mid-nineteenth century, permanent occupation of the Midwest was difficult without the aid of artificial drainage (Beauchamp, 1987). Beginning in the mid-1800s, organized drainage districts and enterprises installed ditches and tile to drain many permanently or seasonally wet areas and create more arable land (Beauchamp, 1987; Skaggs et al., 1994). Between 1850 and 1930 Illinois, Minnesota, and Wisconsin lost an estimated 90%, 53%, and 32% of state wetlands, respectively (McCorvie and Lant, 1993). Enormous tracts of wetlands and tall grass prairie (millions of acres) were levelled and drained, mainly by surface ditches and canals, in the RRB during this same time (Miller and Frink, 1984). Artificial drainage increased property value, and as corn and soybean commodity prices increased, as they did following WWII, in the mid-1970's, and most recently a tripling of commodity prices between 2002-2012 (Glaser, 2016; Johnston, 2013), lands previously cultivated for small grains or left as wet meadows were drained and converted to soybean and corn fields (Blann et al., 2009; Burns, 1954; Wright and Wimberly, 2013). Although many advances in cropping practices have led to the modern day prosperity of the Corn Belt, drainage installation and intensification has played a critical role for agriculture in the Midwestern US. Today the RRB, MRB, CRB, and IRB respectively contain 45%, 78%, 12% and 60% of land cultivated for corn and soybeans, yet estimates of tile drainage in these basins remain poorly constrained (Fig. 1). Within the Bois de Sioux watershed, a sub-basin of the RRB where permits are required for drain tile installation, annual installation has increased from ~~3 miles~~5 km in 1999 to ~~1,924 miles~~3,096 km in 2015 for a cumulative total of ~~15,102 miles~~24,304 km of new tile installed since 1999 (Bois de Sioux Watershed District, 2015). Tile drainage installation in all basins continues to this day.

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The other major anthropogenic impact that affects all basins is dams installed for hydropower, navigation, water resources, and recreation. Most of the dams in our study basins are small and were constructed in the late 1800's and early 1900's (Barnes, 1997; Delong, 2005; Graf, 1999; Hyden, 2010; Lian et al., 2012; Martin, 1965; Stoner et al., 1993; United States Army Corps of Engineers, 2016). Therefore, the effects of these dams would have been established well before our study period. For example, in the Illinois River basin all major dams had been completed by 1939. Based on work by Lian et al. (2012), streamflow changes post 1938, specifically peak flows, have been influenced more by climate than dam operations, though they did not consider the effects of drain tile. One exception might be the uppermost Illinois River basin, which has been influenced by expansion of the Chicago metropolitan area. Though historical and present water withdrawals are largely unknown, increased water use for industry, agriculture, and public drinking supply may offset some of the climate impacts of increased precipitation. Urban and suburban detention basins may also limit how much precipitation is converted to runoff. We expect that other water development projects in each basin have minimally affected streamflows at the basin outlet. Conversion of hay and small grains to corn and soybeans accompanied by artificial drainage expansion are likely the largest land use land cover (LULC) changes in these basins since the early to mid-twentieth century.

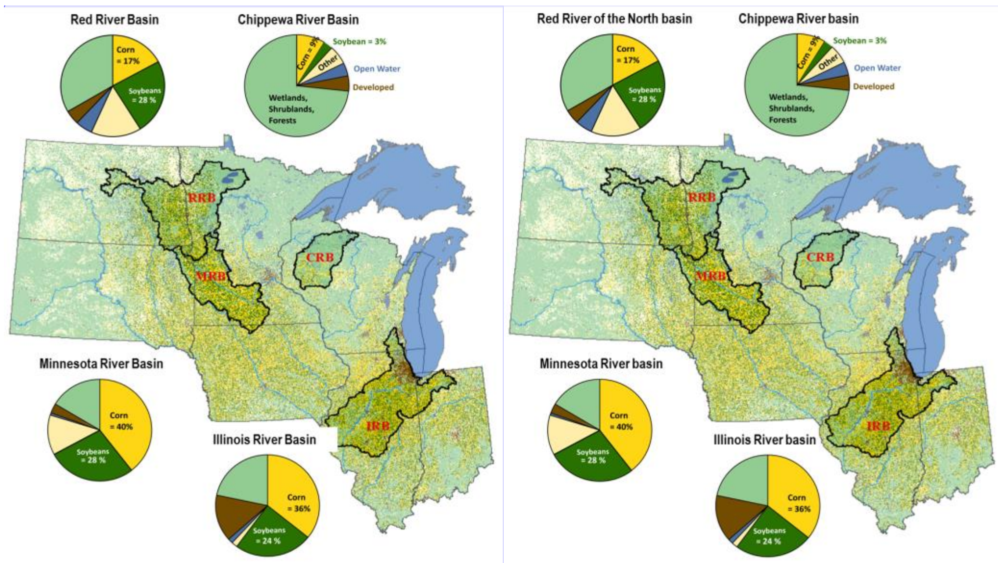

Figure 1: 2013 R~~Cropland Data Layer (CDL) showing the r~~elative proportion of each land cover class for the four study watersheds, Red River of the North basin (RRB), Minnesota River basin (MRB), Chippewa River basin (CRB), and Illinois River basin (IRB) ~~in the Upper Midwest~~. Data from USDA National Agricultural Statistics Service Cropland Data Layer (2013).

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3 Data and Methods: land use land cover, climate, and streamflow

We explain our methods for addressing how land use, climate, and streamflows have changed during the 20th and 21st centuries in sections 3.1 thru 3.3. In section 3.4 we explain how the timing and timescales of prominent change were determined. We use a water budget to determine whether precipitation and evapotranspiration alone can explain runoff trends in section 3.5.

3.1 Records of land use land cover (LULC) change during the 20th and 21st centuries

We compiled county-level US Census of Agriculture drainage data from 1940, 1950, 1960, 1978, and 2012 for each study watershed, weighing partial counties by area (U.S. Bureau of the Census, 1942, 1952, 1961, 1981; U.S. Department of Agriculture, 2014a). Tabulations of drainage enterprises exclude lands draining less than 500 acres in all years except 1940 (U.S. Bureau of the Census, 1922, 1952). In 1940 and 2012, acres drained by ditches and tile were reported individually. To normalize the land area across basins of different sizes, we report the percentage of watershed area drained. While the uncertainties in these data are high, they are the best data available on a national scale for our study period. Some studies (e.g. David et al., 2010) have taken advantage of other drainage estimates, such as those from ~~(~~Sugg, (2007). However, the Sugg (2007) method was calibrated and validated using data from 1987 and 1992 drainage census reports. Therefore it is unclear whether this approach could be used to estimate historical or current drainage extents. Furthermore, the drainage estimates are based on soil type, class, and crop type and assume that state percentages of average cropland area drained are uniform for every county in each state and have remained static through time (Sugg, 2007). Although somewhat tedious, we~~We~~ use U.S. Census of Agriculture drainage~~these~~ data as ~~a~~the best available proxy for the relative drainage extent and expansion through time in each of the four large study basin, the smallest of which is still larger than 20 counties.

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County level agricultural census drainage data are only available for five census years. Therefore, we also compiled annual USDA National Agricultural Statistics Service (NASS) crop acreage harvested in each basin following the methods of Foufoula-Georgiou et al. (2015). We report the percentage of corn, soybeans, and hay and small grains grown in each watershed from 1915 to 2015. Artificial drainage installation has typically coincided with the replacement of hay and small grains for soybeans as shown in Fig. S1 in the Supplement (Burns, 1954; Hewes and Frandson, 1952). Therefore we use these annual crop data as another indication of LULC changes.

3.2 Climate records: precipitation and evapotranspiration

Monthly Parameter elevation Regression on Independent Slopes Model (PRISM) precipitation rasters produced by PRISM Climate Group (2004) and modeled actual evapotranspiration (ET_a) produced by Livneh et al. (2013) are readily available, reproducible, and defensible climatology data that provide continuous spatial and temporal coverage of our study areas. We compiled spatially-averaged monthly and annual precipitation and evapotranspiration depths for each watershed for 1935-2013 and 1935-2011, respectively.

Livneh et al. (2013) evapotranspiration was produced for the continental United States using the Variable Infiltration Capacity (VIC) model run at 3-hr time steps in energy balance mode, consistent with methods of Maurer et al. (2002). Hereafter we refer to Livneh et al. (2013) and Maurer et al. (2002) as L13 and M02. We have chosen L13 data over other available estimates of evapotranspiration because they cover a large spatial and temporal domain necessary for the study, i.e. the contiguous US from 1915-2011, at reasonable spatial ($1/16^{\circ}$) and temporal (monthly) resolution, unlike other global and North American reanalysis products such as ERA-Interim (data available from 1979-2013 at 0.7°) and NARR (data available from 1979-2015 at 0.3°).

Although the precipitation input used to generate the ET_a data was gridded NCDC COOP station data, Livneh et al. (2013) scaled monthly gridded precipitation to match the PRISM long term mean (1961-1990).~~state that “gridded precipitation values were subsequently scaled on a monthly basis so as to match the long term mean from the Parameter~~

~~Elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 1994); for consistency with M02, a 1961–90 PRISM climatology was used".~~ We directly compared monthly precipitation from L13 and PRISM (1935-2011) and found that for each of the four study basins the mean error was 1% (Fig. S3). Further discussion of potential biases in using the ET_a estimates from L13 are discussed in the Supplement.

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3.3 Streamflow gauge records

We evaluated annual (seasonal), monthly and daily flow metrics for each of the four river basins. Using multiple gauges for a single basin, we compiled seven annual flow metrics: mean annual flow, 7-day average annual low flow winter (November-April), 7-day average annual low flow summer (May-October), peak mean daily flow spring (March-May), peak mean daily flow summer and fall (June-November), high flow days, and extreme flow days using mean daily flow data from USGS gauges within each basin (Fig. S2; Table 1) following the methods of Novotny and Stefan (2007). The number of high and extreme flow days refers to the number of days in a given year that are one and two standard deviations above the 1950-2010 mean. For each gauge, we normalized the annual flow metric by the 1950-2010 mean to facilitate comparisons among basins and to observe similarities in trends among metrics. Each gauge record included a minimum of 62 years, and of the 63 gauges analysed 53 gauges had continuous records. Of the 10 non-continuous records, 4, 2, 2, 1, and 1 gauges were missing 2, 4, 6, 8, and 14 years of data respectively during the period 1929-2013 (Table 1).

For the downstream outlet gauge in each basin (Table 1) we computed annual and monthly streamflow average depths (cm month^{-1}) and volumes (km^3 month^{-1}) for 1935-2013 for the MRB, RRB, and CRB, and 1939-2013 for the IRB due to missing gauge data prior to 1939. We also calculated daily streamflow change exceedance probabilities, where $dQ/dt>0$ characterizes the rising limbs of daily hydrographs and $dQ/dt<0$ the falling limbs.

3.4 Determining the timing and time-scales of prominent LULC, climate, and runoff changes

In order to determine whether observed changes in climate and streamflow are statistically meaningful and potentially coincident with LULC change, we first determined the timing of climate, streamflow, and LULC change. Annual crop data reveal the timing of rapid expansion of soybean acreage and indicate land use land cover transitions (LCTs) when soybean acreage exceeds hay and small grains (Foufoula-Georgiou et al., 2015). We identified the timing of precipitation and streamflow change using wavelets and by fitting a piecewise linear regression (PwLR) using a least-squares approach to the monthly streamflow and precipitation volume time series in each basin (Liu et al., 2010; Tomé and Miranda, 2004; Verbesselt et al., 2010; Zeileis et al., 2003).

A common method for detecting and quantifying changes in the magnitude/frequency content of a time series is via a localized time-frequency analysis using wavelets. The Continuous Wavelet Transform (CWT) of a signal $x(t)$ is defined as the convolution of the signal with scaled and translated versions of a mother wavelet $\psi(t)$:

$$T(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt \quad (1)$$

where $\psi\left(\frac{t-b}{a}\right)$ is the mother wavelet scaled by parameter a and translated by parameter b, and * denotes the complex conjugate. By changing a ~~(i.e., dilating or contracting the mother wavelet by a scale factor)~~ and ~~changing~~ b ~~(centering the wavelet at different locations along the time axis),~~ the CWT quantifies the localized energy or variance of a signal at different times and scales (frequencies). To every scale there is a corresponding frequency assigned as the central frequency of the Fourier transform of the wavelet at that scale. This relationship is analytically computable depending on the chosen mother wavelet. In this paper, we use the Morlet wavelet (Addison, 2002; Daubechies, 1992; Seuront and Strutton, 2003), which has been proven effective for analyzing climate signals such as El Niño, streamflow, and precipitation among others (e.g., Anctil and Coulibaly, 2004; Foufoula-Georgiou et al., 2015; Labat et al., 2001; Torrence and Compo, 1998 and the references therein). The Morlet wavelet is~~ given as:~~

$$\cancel{\psi(t) = \frac{1}{\pi^{1/4}}\left(e^{i2\pi f_0 t} - e^{-(2\pi f_0)^2/2}\right)e^{-t^2/2} \quad (2)}$$

~~which is~~ simply a complex wave within a Gaussian envelope and by choosing the central frequency ~~, where~~ f_0 appropriately it simplifies to the form: ~~is the central frequency of the mother wavelet. In practice, when $f_0 \gg 0$, the second term in the parenthesis of Eq. (2) becomes negligible and the Morlet wavelet simplifies to:~~

$$\psi(t) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0 t}\, e^{-t^2/2}. \quad (2\cancel{3})$$

Here we used ~~The Morlet wavelet with~~ $f_0 = 0.849$ as this ~~-~~achieve~~s~~s ~~s~~ the best ~~compromise between~~ time~~- and~~ frequency localization (Addison, 2002). ~~s.~~

We also evaluated precipitation and streamflow change using two statistical tests and three breakpoints. We selected 1974/75 as a breakpoint for the pre-period and post-period because it lumps the time series data into two roughly equal periods (40/39 years), coincides with the timing of widespread acceptance of cheaper and easier to install corrugated plastic tile (Fouss and Reeve, 1987), and other studies in the MRB and IRB have identified hydrologic change occurring around that time (e.g. Foufoula-Georgiou et al., 2015; Lian et al., 2012; Schottler et al., 2014). Acknowledging that 1974/75 may not be the hydrologically relevant breakpoint in all basins at this large scale, we ran statistical tests using 1974/1975 as well as the breakpoints identified for each basin from the PwLR and LCT.

We performed one-tailed student's t-tests or Wilcoxon Rank Sum tests when data did not meet parametric assumptions after testing log, square root, and arcsine transformations, and Kolmogorov–Smirnov (KS) tests using the statistical program R to analyze changes in the mean and distribution of annual and monthly total flow (Q) at the basin outlet and spatially averaged basin precipitation (P) volumes between each pre-period and post-period (R Core Team, 2013). We test the hypothesis that mean monthly water volumes have increased and their distributions have shifted right during the post-period. We selected an alpha value of 0.05 (95% confidence level) for all statistical tests performed. Thus we performed

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312~~286~~ t-test and 312~~268~~ KS-test using the annual and monthly P and Q data for each basin, as well as 28 t-tests on the seven streamflow metrics described in section 3.3 for a total of 652~~00~~ statistical tests. In general the results of the statistical tests are not sensitive to the timing of different breakpoints, spanning nearly four decades, and therefore we generally report statistical results for the pre-period (1935-1974) and post-period (1975-2013), though all results are presented in Table S1 in the Supplement.

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3.5 Determining the role of climate versus LULC change on streamflows using a water budget

For given watershed over a specified time period of integration, water inputs minus water outputs are equal to the change in storage per unit time:

$$P - ET - Q = \frac{dS}{dt} \qquad (3)$$

where P is average watershed precipitation (cm month^{-1}), ET is estimated average watershed actual evapotranspiration (cm month^{-1}), Q is runoff depth at the basin outlet (cm month^{-1}), and $\frac{dS}{dt}$ is the depth of change in soil water, groundwater, and lake/reservoir storage per unit time.

We have computed average annual water budgets for each basin by accumulating monthly P, ET, and Q during the pre-period and post-period determined by the land cover transition (LCT) and 1974/75 in each basin, to solve for the change in storage. If the change in storage term increases from the pre-period to post-period we conclude that soil moisture, groundwater, and/or lake/reservoir storage has also increased and that climate likely explains most of the increase in Q. However, if the change in storage term decreases from the pre-period to post-period, then we conclude that soil moisture, groundwater, and/or lake/reservoir storage has decreased despite precipitation increases, indicating that widespread LULC change has altered watershed storage and contributed, in addition to precipitation, to increased streamflows.

Livneh et al (2013) did not incorporate land use land cover changes, such as tile drainage expansion or crop changes, into the VIC model. The fact that LULC change is not included in the model is what allows us to test, external to the ET predictions, whether or not a LULC effect exists. There is no evidence of regional groundwater change and the effects of dams and urbanization on streamflows are likely minimal as discussed in section 2. Comparing these data to other estimates of evapotranspiration including four AmeriFlux towers, two of which are in corn-soy agricultural areas, we demonstrate that they are sufficiently reliable modern estimates for our purposes (Table 2; Fig. S4; Fig. S5).

We acknowledge that there is uncertainty in the all of the input data and understand that the magnitude of the storage term is sensitive to estimates of ET. Livneh et al. (2013) reported 17% overestimation of ET_a during the summer months when compared with AmeriFlux station data. It is during summer months that ET is most likely limited by soil water availability. Therefore in addition to the raw water budgets, we present water budgets where we have reduced monthly ET_a by 17% during summer months (JJA). This lower estimate of ET effectively reduces the potential amount of streamflow change that could be attributed to land use and artificial drainage and is therefore a more conservative analysis. Overall, the data from Livneh et al. (2013) used in computing the monthly water budgets are consistent with other sources (Bryan et al., 2015; Diak et al., 1998) and provide reasonable modern estimates of ET_a, especially when reducing summer (JJA) ET_a by 17% (Figs. S4 & S5).

4 Results and Discussion

4.1 Drainage, corn and soybean expansion during the 20th and 21st centuries in the Upper Midwest

Across the Upper Midwest, the percent of land drained by tiles and ditches and cultivated for corn and soybeans has increased since the early twentieth century while land cultivated for hay and small grains has declined. Figure 2 shows the percent of each watershed drained by tiles and ditches from the Census of Agriculture data, as well as the percent of each county drained by tile in 1940 and 2012. Total drainage and tile drainage has increased in the MRB and IRB, while it has remained relatively unchanged from 1940 to 2012 in the CRB and RRB (Fig. 2). The drainage census data show that the MRB has the greatest percentage of the watershed area drained by tile, 19% in 1940 and 35% in 2012, and ditches, 7% in 1940 and 10% in 2012, followed closely by the IRB ~~where tiles drained 10% and 34% of the watershed area in 1940 and 2012, respectively, and ditches drained 12% and 8% of the watershed area in 1940 and 2012, respectively~~ (Fig. 2). The Red River of the North basin has experienced very little increase in total drainage since 1940. Most artificial drainage in the RRB is ditches rather than tile drains. Although a dramatic increase in tile installation has been reported in the Red River Valley since the 1990's, the area of this expansion appears small relative to the watershed area. Acres reported to be drained by tile in 2012 represents only 2% of the total watershed area. The ~~Chippewa River Basin~~CRB has very little agricultural land and thus the 2012 census reports less than 1.5% of the watershed area drained by tile and ditches (Fig. 2).

The 1978 census data illustrate the uncertainty associated with reporting~~ and response rates~~, as it is unlikely for total drainage to have decreased between 1960 and 1978 in the RRB and MRB (Fig. 2). Most county ditches and tile in Blue Earth County, Minnesota were installed during the 1910's and 1920's with a noticeable drop off during WWII and a resurgence of drainage enterprises starting in the 1960's (Blue Earth County Minnesota, n.d.). Burns (1954) reported that the 1940 census data underestimated drainage enterprises in Blue Earth County by 8.5%, simply due to inaccuracies in reporting. According to one report, it was estimated that 27% of drained land in the United States was not included in the 1960 drainage census due to private drainage operations on lands less than 500 acres (Gain, 1967). Furthermore, ~~in 2012,~~ 82%, 80%, 51%, and 91% of all farms in Minnesota, Illinois, North Dakota, and Wisconsin, respectively, were less than 500 acres in 2012, and therefore were not included in survey results (U.S. Department of Agriculture, 2014b). Therefore these estimates are likely to underestimate the area drained by tile and ditches. Although the 2012 census attempts to correct for incomplete and missing responses, because drainage enterprise records have traditionally been so poorly documented, it is difficult to know how much reported acreage underestimates the actual acreage.

We also note that acres drained by tile and ditches does not directly translate to effectiveness of artificial drainage ~~at transferring soil water to streams~~. Several factors influence the flow rate from soils, ~~to drains~~ including the hydraulic conductivity of the soil, ~~prevalence of soil~~ macropores, depth of the water table, depths of the tile lines, tile diameter ~~of the tile~~, slope of the tile or ditch, horizontal spacing ~~of tiles and ditches, material composing the tile or ditch~~, as well as precipitation intensity and duration and antecedent soil conditions (Hillel, 1998). We simply do not have this level of information regarding artificial drainage in the Midwestern USA and suspect that the spatial variability in drainage management practices may be high. For example, Naz et al. (2009) mapped tile drains in a 202 km^2 Indiana watershed and found tile spacing that ranged from 17-80 m.

While we expect that the drainage trends observed are relatively correct, we are cautious about drawing any definitive conclusions from the Census of Agriculture data regarding the actual extent of tile drainage and changes over time. It is clear that these estimates tend to underestimate the amount of drainage. Nevertheless, total drainage and tile drainage in the Minnesota River basin and Illinois River basin have increased considerably since 1940. It is known anecdotally, but not included in these data, that tile drainage spacing has decreased and intensity or drainage rate in mm h^{-1} has increased on agricultural lands, often by a factor of two, as was done at the Lamberton Research Station, MN (L. Klossner, personal communication, November 17, 2015). ~~Overall we find artificial drainage extent greatest in the MRB and IRB, relatively low, but growing recently in the RRB, and negligible in the CRB. While relative amounts of drainage in this inventory should be reliable, the lack of historical documentation on changes in location, density and type of tile installed limits our ability to model hydrologic change at the large landscape scale.~~

Conversion from small grains to soybeans is often accompanied by increased sub-surface drainage installation (Foufoula-Georgoiu et al., 2015). Figure 3 displays the percent of each basin harvested for corn, soybean, and hay and small grains from 1915-2015. There has been a decline in hay and small grains and an increase in soybeans in all four of the watersheds over the period of record. The RRB is the only basin containing a significantly higher percentage of soybean acreage relative to corn; on average since 1995 soybean acreage in the RRB has been more than twice that of corn.

Overall, changes in crop type occurred gradually in the MRB and IRB, much more rapidly and recently in the RRB (Fig. 3). The CRB is largely non-agricultural, only 9% of the basin grew corn, soy, and hay and small grains in 2015, and the changes in the basin have been small during the period of record (Fig. 3). While we cannot directly ascribe these changes in crop type to changes in drainage practices or vice versa, they provide a relatively detailed history of LULC and whether the changes occurred gradually or rapidly and recently or long-ago in each basin.

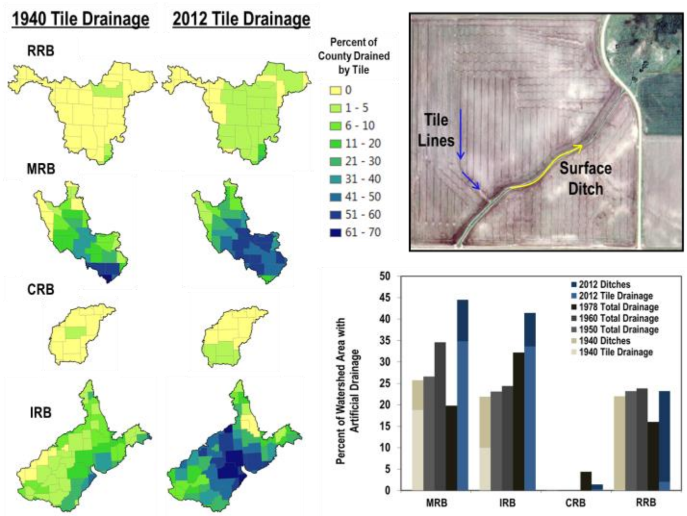

Figure 2. At left: Spatial distribution of tile drainage patterns ~~in each of the four study basins~~ in 1940 and 2012 for each of the four study basins: Red River of the North basin (RRB), Minnesota River basin (MRB), Chippewa River basin (CRB), and Illinois River basin (IRB). Upper right: image showing an example field pattern that combines subsurface tile lines with a surface ditch. Lower right: Percentage of the total watershed area with artificial drainage from 1940, 1950, 1960, 1978, and 2012 drainage census data. The magnitude of each bar indicates total drainage (ditches and tiles), and 1940 & 2012 bars are broken proportionally into drainage by ditches and tiles.

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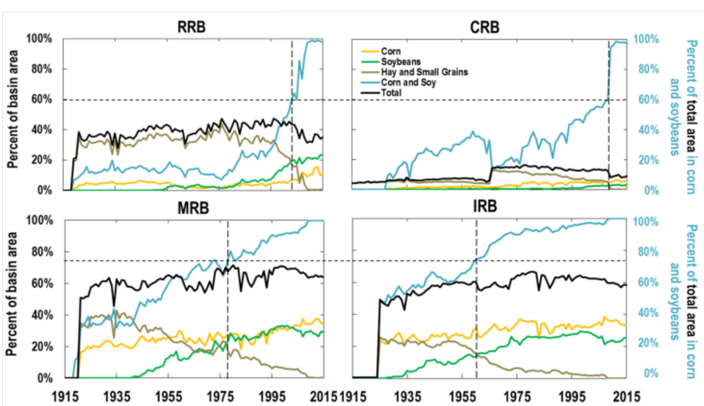

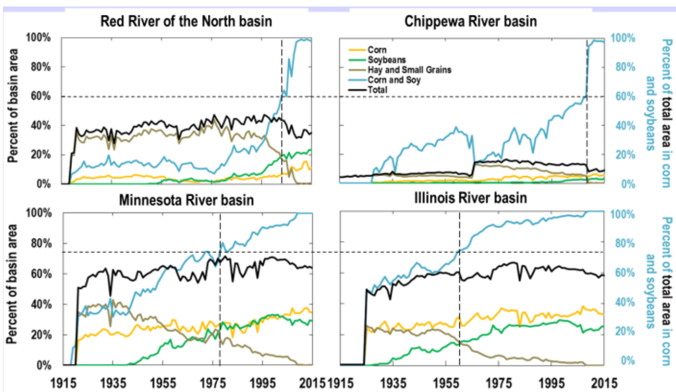

Figure 3. Acres harvested of corn, soybeans, and hay and small grains (barley, oats, wheat) expressed as percent watershed area for each of the basins based on county level data from USDA NASS. The sum of these three commodity groups is shown as a total in black and the percent of this total area in corn and soybeans is plotted in blue. Vertical dashed lines indicate when percent of basin area harvested for soybeans exceeds hay and small grains. Horizontal dashed lines indicate when the percent of total area harvested for corn and soybeans exceeds 60% in the Red River of the North basin ~~RB~~ and Chippewa River basin~~B~~ and 75% in the Minnesota River basin ~~B~~ and Illinois River basin~~B~~.

4.2 Timing of streamflow change coincides more closely with precipitation than land cover change

The land cover transition (LCT), precipitation, and streamflow breakpoints of change identified using piecewise linear regression (PwLR) and continuous wavelet transform (CWT) reveal that the timing of precipitation and streamflow change generally preceded LCT change (Table 3). This was true for all tests in the RRB and CRB. However, there are some chronical differences in the order of precipitation, streamflow, and LCT breakpoints. In the IRB, the timing of LCT precedes precipitation and streamflow breakpoints identified using PwLR and CWT by between 13 years and 20 years (Table 3). In the MRB, LCT follows precipitation by 20 years and streamflow by 11 years as identified using PwLR but precedes the streamflow breakpoint by one year identified using CWT (Table 3).

Land cover transition breakpoints shown in Fig. 3 are not exact; land cover change occurs gradually, and therefore LCT breakpoints represent when a large portion of each watershed was converted to from hay and small grains to soybeans. Land cover transition breakpoints are indicated two ways: 1) when percent watershed area harvested for soybeans exceeds hay and small grains, and 2) when the proportion of the total acreage harvested for the three commodity groups is dominated by corn and soybeans. The second criteria varies from basin to basin, as some basins may have historically grown more hay and small grains, while others more corn and soybeans. In the CRB and RRB, hay and small grains exceeded 50% of the total area harvested for corn, soybeans, and hay and small grains from 1915 until the year 2000 or later. However in the MRB and IRB, hay and small grains only exceeded 50% of the total area harvested for the three commodity groups from 1915 until 1950 or earlier. The LCT breakpoints, indicated by the vertical dashed lines in Fig. 3, approximately coincide

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with the horizontal dashed lines, which represent a time when the percent of the total acres harvested for the three commodity groups exceeded 60% in RRB and CRB, where hay and small grains have historically dominated, and 75% in the MRB and IRB, where corn and soybeans have historically dominated. We acknowledge that these breakpoints do not consider the actual extent of soybeans, which is assumed to be a surrogate approximation for area of drained croplands. Soybean coverage is much higher for both MRB and IRB compared to RRB and CRB even before 1955. Considering the large proportion of the MRB and IRB watersheds cultivated for soybeans in the early 1950's combined with extensive (20-25%) drainage by 1940 and 1950 (Fig. 2), this suggests streamflow changes generally occurred after both precipitation and LCT changes.

We observe minimal changes in the energy of the annual and inter-annual precipitation signal for any basins during the period of record, and therefore could not identify the timing of precipitation change in any basin using CWT (Fig. 4). However, Figure 4 displays significant increases in the annual and inter-annual energy of the basin outlet streamflow signal around 1975, 1980, and 1995 for the IRB, MRB, and RRB respectively, while the CRB does not exhibit any striking changes in energy throughout the period of record. All decadal energy shifts in the precipitation signals are clearly translated into the decadal energy of the streamflow signals for all four basins (Fig. 4). The observed correlation between the decadal energy changes in streamflow and precipitation signals together with the lack of any significant correlation between their energies at the annual scale may signal the importance of factors other than precipitation, here artificial drainage, to streamflows in the MRB, RRB, and IRB at the annual scale.

In all basins, the timing of precipitation change coincided with or preceded streamflow breakpoints based on PwLR (Table 3). Similar temporal coincidence of precipitation and streamflow breakpoints in contrast to the LCT and streamflow breakpoints may suggest that streamflow changes are tightly coupled with precipitation changes. However, that interpretation fails to account for the potential effects of drainage, which could amplify the streamflow response to precipitation.

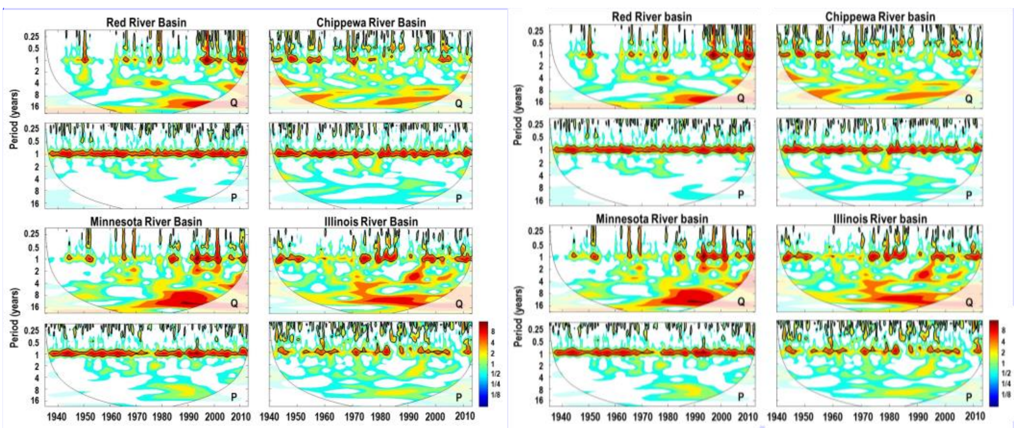

Figure 4. Continuous Wavelet Transform (CWT) energies for monthly volumetric streamflow (Q) and precipitation (P) time series.

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4.2.1 Seasonal and annual scale changes of precipitation, evapotranspiration, and streamflow

The raw timeseries of spatially averaged annual precipitation and streamflow depths (cm), reported in the Supplement, show an increasing trend in precipitation and streamflow in the RRB, MRB, and IRB and no trend in the CRB (Fig. S6). The magnitude of the precipitation and streamflow trends are on the order of 120-150 mm/century and 90-170 mm/century, respectively, and are consistent with those reported for the entire Upper Mississippi River basin by Frans et al. (2013). ~~(~~Xu et al.~~,~~ (2013) report precipitation trends that are similar to our study and Frans et al. (2013) in 22% of the study watersheds (average size 489 km^2) in Iowa, Illinois, Indiana, and Ohio. Figure 5a shows five year running averages of seven annual streamflow metrics, where normalized values of 1 indicate that the annual value is equivalent to the mean (1950-2010) value. Stationary flow statistics vary around 1 for the entire time series, as is the case for the Chippewa River basin (Fig. 5). Non-stationary time series systematically deviate from 1, indicating that the mean condition has changed during the period of record. Qualitatively, all seven flow metrics in the CRB have remained stable since the 1930's, except for seven day low flows in winter, which have increased 12% since 1975 (p<0.01) (Fig. 5).

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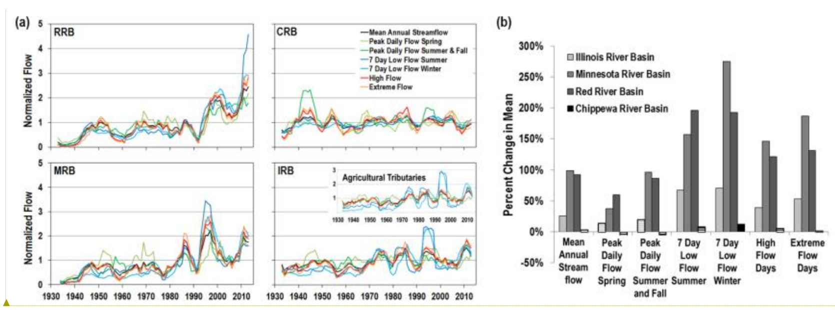
Unlike the Chippewa, flow metrics in the Minnesota, Red, and Illinois river basins systematically increase in recent decades, with nearly a two-fold increase or greater in almost all flow metrics since 1975 (Fig. 5). Seven day low flows in summer and winter (i.e. the lowest annual flows) have increased most in these basins~~;~~, where mean~~s~~ conditions have increased 67%-275% (p<0.001) since 1975 (Fig. 5b). In much smaller basins, Xu et al. (2013) also reported the greatest streamflow changes to baseflows. High flow and extreme flow days have also increased significantly in the MRB (p<0.001), IRB (p<0.05) and RRB (p<0.001). Spring peak daily flows have changed the least in all basins, indicating 14% (p>0.05), 37% (p<0.05), and 60% (p<0.05) increase in mean between 1934-1974 and 1975-2013 for the IRB, MRB, and RRB, respectively (Fig. 5b). The Minnesota River basin has seen the greatest percent increase in mean annual flow, peak daily flow summer & fall, 7 day low flow in winter, high flow days and extreme flow days (Fig 5b). Peak daily flow summer and 7 day low flow in summer have increased most in the Red River of the North basin (Fig. 5b).

All seven flow statistics in the Red River of the North basin increase dramatically after the mid-1990's (Fig. 5a). Low flows have increased 3.5-4 fold (p<0.001) and high and extreme flows have increased 2.5-3 fold (p<0.001) in the RRB since 1995 (Fig. 5b). Flows in Minnesota River basin have increased similarly, with a 3-4 fold increase in low flows (p<0.001) and 3 fold increase in high and extreme flows (p<0.001) since the timing of land cover transition. Changes in the Illinois River basin are less obvious, yet still significant, with a 2 fold increase in low flows (p<0.001) and 1.5 fold increase in high and extreme flows (p<0.05) since LCT.

The MRB and RRB exhibit an increase not only in the magnitude but also in the cyclicity and synchronicity of these metrics after about 1980 (Fig. 5a). Cyclicity could imply that climate is playing a role in the observed increase in flows. However, the extent to which agricultural land and water management practices may be amplifying this climate effect cannot be ascertained from this figure alone. The Illinois River basin exhibits the most change in summer and winter 7 day low flows, which increase after 1970, and this trend is even more pronounced when only examining gauges within predominantly agricultural sub-basins that are unaffected by large dams (Fig. 5a). However, the changes in the RRB and MRB are much more obvious and statistically significant than those in the IRB.

Statistical results for annual changes in streamflow and precipitation for all breakpoints can be found in Table S1 in the Supplement. The following results are based on the 1974/75 breakpoint. Overall, average annual streamflow, precipitation, and evapotranspiration depths have increased significantly in the MRB and RRB, while only streamflow has increased significantly in the IRB; no significant changes are reported in the CRB. Average annual runoff depth at the outlet gauge of the MRB has increased 5.9 cm (p<0.001). Average annual precipitation and evapotranspiration depths in the MRB have also increased by 4.6 cm (p=0.033) and 3.3 cm (p=0.021), respectively. Average annual runoff ratio has increased from 0.11 to 0.18, equivalent to a 65% increase and consistent with the results of Vandegrift and Stefan (2010). In the RRB, the average annual runoff ratio has increased 65%, from 0.07 to 0.11 at the outlet gauge, which is slightly greater than the 55% increase reported by Vandegrift and Stefan (2010). On average, annual runoff, precipitation, and evapotranspiration depths have increased by 2.9 cm (p<0.01), 4.1 cm (p=0.019), and 2.4 cm (p=0.043), respectively. Average annual runoff in the IRB has increased 5.4 cm (p=0.011). Precipitation and evapotranspiration are likely increasing in the IRB, however given the statistical power the apparent 4.2 cm (p=0.086) and 1.9 cm (p=0.072) increases were not significant. The average annual runoff ratio in the IRB has increased from 0.30 to 0.34, a 14% increase. The CRB average runoff ratio has decreased slightly (2%), from 0.37 to 0.36. On average, annual runoff depth in the CRB has not changed (0.00 cm; p=0.499). Average precipitation and evapotranspiration depths may have increased slightly, perhaps as much as 2.0 cm (p=0.243) and 0.9 cm (p=0.209) respectively, but these changes were not statistically significant.

The MRB and RRB exhibit the greatest change in the annual runoff ratio, followed by the IRB, with negligible change in the CRB. These findings are consistent with the fact that the MRB and RRB have relatively low runoff ratios comparted to the CRB and IRB, and are the only two basins where annual precipitation and evapotranspiration increases were statistically significant. On average, the fraction of annual precipitation that goes as ET has decreased 1.0%-2.4% in all four study basins, which is smaller in magnitude but consistent in direction of change with Schottler et al. (2014) who found the ratio of PET/P decreased 5.6% between 1940-1974 and 1975-2009 in a subbasin of the MRB. Schottler et al. (2014) considered the effects of both climate and cropping practices in calculations of PET while the Livneh et al. (2013) calculated ET_a only considering climate. Modern decreases in PET/P ratios in Midwestern agricultural watersheds are also reported by Xu et al. (2013).



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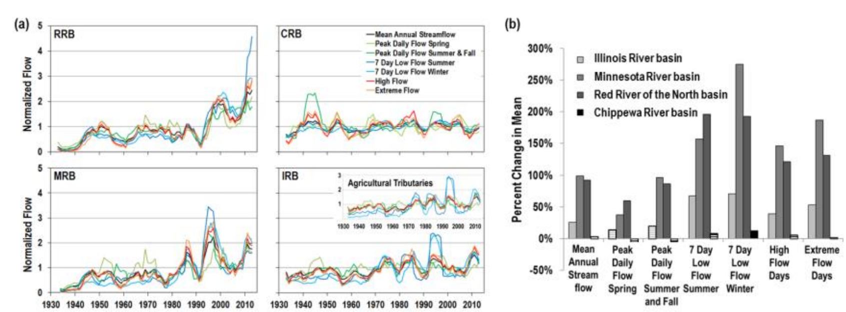

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Figure 5. a) Seven normalized streamflow statistics presented as five year running averages based on annual and daily gauge analysis for the Red River of the North basin (RRB), –22 gauges~~)~~;~~,~~ Chippewa River basin (CRB), —9 gauges~~)~~;~~,~~ Minnesota River basin (MRB)~~–~~, 12 gauges~~),~~; and Illinois River basin (IRB), –20 gauges~~);~~. IRB inset of same metrics, but for 7 tributary gauges~~,~~ that are predominately agricultural~~,~~ and not influenced by major dams. b) Percent change in flow metric mean between 1934-1974 and 1975-2013. Solid bars indicate significant increases in means (alpha=0.05). Annual flow metrics normalized by the 1950-2010 mean.

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4.2.2 Monthly scale changes of precipitation, evapotranspiration, and streamflow

Cumulative monthly precipitation, plotted in Fig. 6, indicates no systematic change in cumulative precipitation with time (i.e. constant slope) for any basin. However, cumulative monthly streamflow (1935-2013) plotted in Fig. 6 indicates a sudden change in slope around 1973 in the IRB, 1980 in the MRB, and 1995 in the RRB, without a distinct change in slope in the CRB. The visually identified change points are consistent with those identified from the CWT (Fig. 4).

Statistical tests of monthly streamflow and precipitation resulted in the same interpretations for 95% of the tests regardless of the breakpoint (Table S1); therefore Fig. 7 summarizes the results of these statistical tests for flow and precipitation in all basins using the 1974/75 breakpoint. Figure 7a illustrates the kernel density estimation, or non-parametric estimation of the probability density function, during the pre-period and post-period for June and September flows in each basin. Figure 7b reports 192 results (48 p-values reported per basin) from the monthly streamflow and precipitation t-tests and KS tests. Each color wheel displays 24 results, 2 results per month for each basin, and shows significant p-values for t-tests and KS tests based on color. Color is inversely related to p-value such that smaller p-values and thus more significant results are shown in increasingly darker colors, with p-values greater than 0.05 colored white. As such the streamflow color wheel in Fig. 7b for the Chippewa River basin is completely white, indicating there were no statistically significant changes in the mean or distribution of monthly streamflow volumes for any months, consistent with the assessment of the seven annual streamflow metrics and cumulative streamflow (Figs 5 and 6). We report a significant increase in mean October precipitation in the CRB. Monthly results for flow and precipitation changes in the CRB are consistent with the annual changes reported earlier.

In stark contrast to the CRB, the streamflow color wheels for the MRB and RRB show significant changes in mean and~~or~~ distribution of monthly streamflow for nearly all months (22 out of 24 for MRB and 21 out of 24 for RRB) (Fig. 7b). In the RRB, mean precipitation in October has increased, and the precipitation distributions have shifted to the right for September and October (Fig. 7b). In the MRB, there has been a significant increase in mean March precipitation (Fig. 7b). The IRB exhibits fewer overall changes in streamflow than the RRB and MRB, with significant changes in monthly streamflow volumes for September, October, November, December and March, and significant changes in August and November precipitation (Fig. 7b).

We acknowledge that due to high variability and small sample sizes, we may not have sufficient power to detect small, but real changes in precipitation and streamflow using these statistical tests, and thus may be prone to Type II error (Belmont et al., 2016). However, these results are consistent with the qualitative assessment of CWT, results of the seven annual flow statistics, and cumulative precipitation and streamflow trends, which indicate only slight changes in total precipitation across all basins, large increases in total flow in the MRB and RRB, moderate flow increases in the IRB, and no streamflow changes in the CRB (Figs 4, 5, and 6).

To understand whether the cause and effect interconnection of streamflow (Q) and precipitation (P) has changed we plotted the joint probability distribution functions (joint PDF) of monthly P and Q, *f(P, Q)*, for each basin (Fig. 8). Joint PDF of pairs of monthly P and Q is the chance of their occurrence simultaneously. In Fig. 8 we illustrate three empirical quantiles of the joint PDFs through contour levels $\alpha \in \{0.1, 0.6, 0.9\}$, where each contour level represents the boundary of a discrete 2D space in which the probability of each (P, Q) pair to fall inside that 2D space is alpha. A shift in the contour levels in the vertical, rather than diagonal, direction suggests that changes in precipitation magnitude alone cannot explain changes in streamflow, and some other component of the system must be amplifying the transformation of precipitation to runoff at the monthly timescale.

There is a shift toward larger monthly streamflow volume for the same volume of precipitation at each 10% and 60% quantile in the MRB and 60% and 90% quantile in the RRB (Fig. 8). However it appears the 90% exceedance contour for the MRB and 10% exceedance contour for the RRB have shifted up and to the right, indicating that an increase in precipitation in the driest months in the MRB and wettest months in the RRB could also be driving some of the change in flow (Fig. 8). Certainly the largest observable change in the MRB and RRB during this time is a shift from small grains to soybeans and an increase in the density and efficiency of drain tile networks. While analyses shown above documented significant changes in streamflow of IRB (Figs. 4, 5, 6, and 7b), this change is not as obvious in these joint PDF contours, which indicate only a slight vertical shift in all quantiles (Fig. 8). Consistent with other analyses, the CRB does not demonstrate any shift in the P-Q relation suggesting the streamflow has been largely unaffected by the observed slight increase in annual precipitation in the basin (Fig. 8).

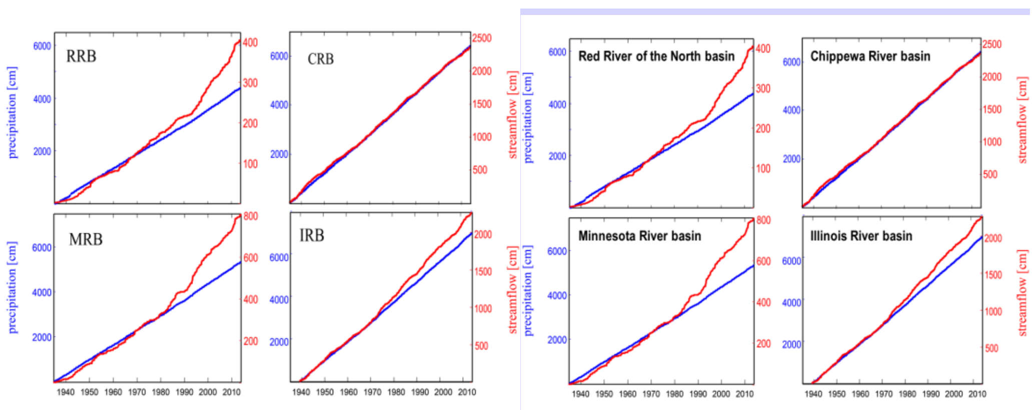

Figure 6. Cumulative monthly precipitation (blue) and streamflow (red) depths (cm) for each river basin. Breakpoints, where the streamflow-precipitation relationship starts to change, are hard to detect from the time series alone but can be clearly seen from

the cumulative plots of the monthly data (i.e., when similar increments of monthly precipitation are translated into larger amounts of monthly streamflow).

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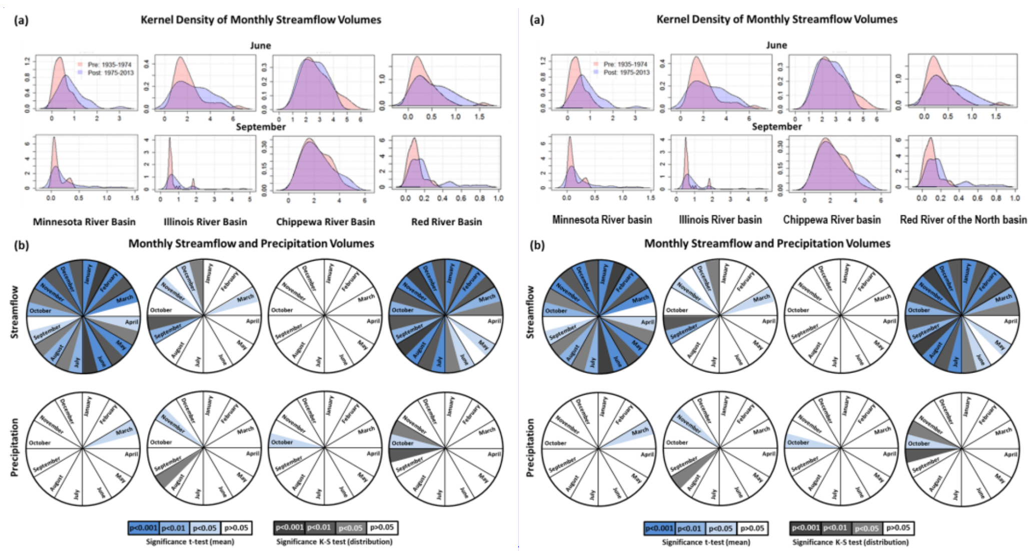

Figure 7. a) Kernel density plots of monthly streamflow volumes for June and September for each basin b) Corresponding significance results for t-tests and Kolmogorov–Smirnov (K-S) tests (α=0.05) of monthly streamflow and precipitation volumes in each basin, where a significant result indicates a positive shift (increase) in the mean or distribution between 1935-1974 and 1975-2013.; color wheels collectively display 192 individual p-values.

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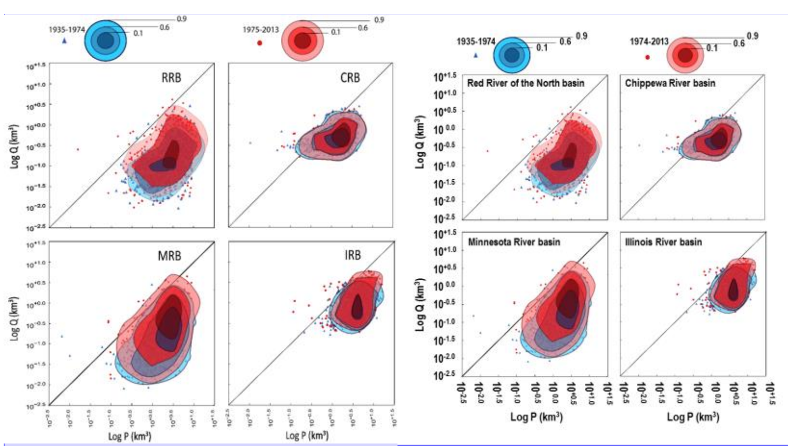

Figure 8. Log-log empirical quantiles of joint PDF plots of monthly streamflow (Q) versus monthly precipitation (P) volumes for each river basin during the pre-period (blue: 1935-1974) and post-period (red: 1975-2013); bulls eye shading represent the 0.1 (dark), 0.6 (medium), and 0.9 (light) confidence intervals.

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4.2.3 Daily scale changes of streamflow

At the daily scale, we found an increase in the magnitude of streamflow change (hydrograph slopes) for both the daily rising limbs (dQ/dt>0) and falling limbs (dQ/dt<0) of the hydrographs for RRB, MRB, and IRB outlet gauges, suggesting an increase in "flashiness", or daily rate of change, of the hydrologic response (Fig. 9). ~~Although the greatest average daily rates of change are less in the post-period than pre-period in the MRB for probabilities of exceedance less than 0.2%, this constitutes a small fraction of the total observations and can be linked to extreme events (Fig. 9).~~ Figure 9 shows a slight decrease in the post-period curve for the CRB, indicating that the rising limb and falling limb flows may actually be less "flashy" in recent times than in the past. May-June is approximately the start of the growing season for soybean and corn and it is the time that tiles are most active, as this time of year usually corresponds to high monthly rainfall, high antecedent moisture conditions from spring snowmelt, and lower ET rates than the peak growing season due to lower crop water demands, and air temperatures that precede the annual peak. ~~Considering rising and falling limbs exclusively in May-June, the magnitude of changes are even greater than the "all months" period for the MRB and RRB (Fig. 9). May-June "flashiness" decreased for the same time period in the CRB.~~

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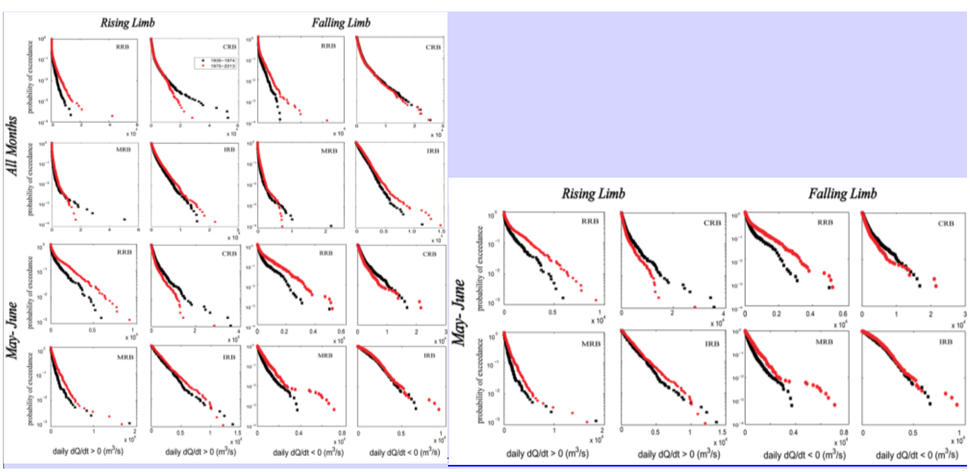

Figure 9. Daily streamflow change exceedance probabilities, where daily (dQ/dt>0) characterizes rising limb flows and daily (dQ/dt<0) characterizes falling limb flows. ~~**Exceedance probability is computed for all months of the year (top two rows) and only May-June (bottom two rows) separately.**~~ **Study basin acronyms are defined as follows: Red River of the North basin (RRB), Minnesota River basin (MRB), Chippewa River basin (CRB), and Illinois River basin (IRB).**

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4.3 Hydrologic budgets suggest declining watershed storage in agricultural basins

While time series and statistical analyses reveal useful insights regarding the timing, magnitude, and significance of precipitation and streamflow changes, as well as provide a qualitative indication of whether or not changes in precipitation and streamflow may be correlated and proportional, they cannot fully deconvolve or attribute the influence of artificial drainage and climate on streamflows (Harrigan et al., 2014). Therefore, we calculate water budgets for each basin as a tool to understand whether the observed changes in precipitation are large enough to account for the changes in streamflow, and if there is more or less watershed storage in recent times than in the past (Healy et al., 2007).

Table 4 reports the calculated average annual water budget terms – precipitation, streamflow, evapotranspiration, and change in storage – during the periods before and after the 1974/1975 and LCT breakpoint using raw and conservative (reduced by 17% in JJA) estimates of ET_a. We find that regardless of the breakpoint or raw vs. conservative estimates of ET_a there is a net reduction in water stored in soil, groundwater, and/or lakes, wetlands, or reservoirs between the pre period and post period in the MRB, RRB, and IRB (Table 4). The most parsimonious explanation for this reduction in water storage is the systematic removal of wetlands and lowering the water table, accomplished through tile drainage installation and expansion.

The CRB, which is not intensively drained (Fig. 2) and has experienced little change in crop type (Fig. 3), has been subject to an increase in precipitation, but does not exhibit an increase in runoff (Table 4), consistent with Figs. 8 & 9b. The overall trends in the CRB water budget indicate that water storage may have actually increased slightly between the pre-period and post-period, which could be accomplished through increased soil moisture, groundwater recharge, or reservoir storage in recent times.

Using conservative estimates of summer ET_a the change in storage term has decreased by about 200%, 100%, and 30%, in the MRB, IRB, and RRB from the pre-LCT-period to post-LCT-period. In the CRB, change in storage has increased by roughly 30% from 1935-1974 to 1975-2011. These results are consistent with our hypothesis that increases in artificial drainage in the MRB, RRB, and IRB necessarily change how precipitation is transformed into streamflow and that increases in precipitation alone cannot explain changes in streamflow in these basins. Without pervasive artificial drainage in the CRB, while precipitation has increased slightly, flows have not changed, likely due to increases in soil moisture, groundwater, and/or lake, wetland and reservoir storage. Seasonal changes in storage shown in Fig. 10 suggest that soil moisture, groundwater, and/or lake, wetland, and reservoir storage in the spring and summer is negative, suggesting not enough P given ET_a to produce observed flows, and positive in the fall suggesting more P and ET_a than necessary to produce observed flows and thus an increase in storage during the fall.

The Red River of the North and Minnesota River basins have some of the poorest drained soils of the Upper Midwest and historically grew more hay and small grains than the other basins (Fig. 3). The introduction of artificial drainage combined with the replacement of hay and small grains with soybeans and the lack of major dams and municipal and industrial water use, has resulted in pronounced streamflow amplification in response to land use and climate changes in the RRB and MRB relative to the IRB and CRB (Fig. 4). Additionally these two basins have seen greater changes in annual and even monthly precipitation (Figs. 7 and 8). However, the extensively drained Minnesota River Basin has seen the largest increases in flow and largest decrease in watershed storage for relatively similar climatic change to the IRB and RRB, and this is likely because of the high degree of watershed hydrologic alteration and connectivity from drainage and lack of other anthropogenic water uses.

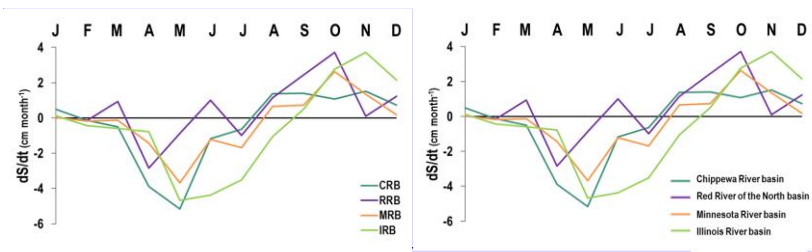

Figure 10. Average monthly (January – December) ~~ds/dt~~change in basin soil moisture, groundwater, and/or reservior storage (ds/dt), calculated after ~~LCT~~land cover transition (LCT) years (see Table 3 for Illinois River basin~~IRB~~, Minnesota River basin~~MRB~~, and Red River of the North basin~~RRB~~ LCT years), and after 1975 for Chippewa River basin~~CRB~~ assuming 17% reduction in ET$_a$ for summer months.

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5 Interpretations, implications, and conclusions

The combined results of this study lead us to three conclusions regarding artificial drainage, climate, and streamflow change in the Upper Midwest during the 20th and 21st centuries: 1) widespread drainage expansion and intensification, especially of tile drainage, coupled with conversion of hay and small grains to corn and soybeans is evident and continues to occur in agricultural river basins; 2) annual precipitation and evapotranspiration have increased since 1975, though we found these changes to only be statistically significant in the MRB and RRB; monthly precipitation increases are generally not significant except in fall months; 3) across multiple scales (daily, monthly , annual) and for a range of flows (low, mean, extreme) streamflows have increased at all times of the year in intensively managed agricultural watersheds (IRB, MRB, and RRB) and have remained stationary in the more forested CRB. The magnitude and timing of precipitation increases in each watershed suggests that precipitation ~~strongly~~ contributes to recently observed increases in streamflow, ~~and agrees~~consistent with other ~~the~~ findings in the Midwestern USA ~~Upper Mississippi River basin (UMRB)~~ (Frans et al., 2013; Xu et al., 2013). Despite this apparent correlation, the magnitude of precipitation increases alone cannot explain the observed increases in flow for agricultural basins according to the water balances. Therefore, it appears that the pervasive and extensive artificial drainage in agricultural basins has contributed to increased streamflow, not only at 10^2-10^3 km watershed scales (e.g. Foufoula-Georgiou et al., 2015; Harrigan et al., 2014; Schilling and Libra, 2003; Schottler et al., 2014; Xu et al., 2013, Zhang and Schilling, 2006), but also at the scale of very large basins studied here.

Harrigan et al. (2014) recognize that often multiple drivers explain hydrologic change. These drivers are not mutually exclusive and may even act synergistically to explain observed streamflow trends. In the Midwestern USA possible explanations that could explain substantial streamflow increases include: 1) changes in storm duration and intensity or the amount of precipitation falling as rain versus snow, have changed the characteristics of runoff generation while having little change on monthly or annual precipitation magnitudes; 2) increases in precipitation have translated into increases in soil moisture, which contributes to amplified flows; and 3) artificial drainage more efficiently routes sub-surface flow to streams, an effect which could be amplified by increased precipitation.

First, it is theoretically possible to observe changes in streamflow while having no change in monthly or annual precipitation magnitudes. High intensity, short duration events yield higher runoff ratios in poorly drained soils. Additionally warmer winter temperatures, earlier snowmelt, and more days when winter precipitation falls as rain instead of snow should affect and even increase winter baseflows, decrease the timing of ice break-up, and affect the magnitude of snowmelt floods. Several studies have documented such hydroclimate changes in the Midwestern USA (Feng and Hu, 2007; Groisman et al., 2001; Higgins and Kousky, 2012) and the role of these hydroclimate changes could be explored by future investigations.

Second, increased soil moisture is known to cause a nonlinear increase in runoff generation for similar precipitation events. Meyles et al. (2003) and Penna et al. (2011) report a threshold response in runoff generation when antecedent soil moisture exceeds ~~~~~65% of the soil porosity. It is possible that soil moisture has increased throughout the Midwestern US. However, no theory exists to predict how big this effect could be on landscape scales (>10^4 km^2). Furthermore, there are very limited data to determine whether or not soil moisture has in fact increased beyond such a threshold despite the immense amount of additional tile drainage that has been installed in the past few decades. Investigating this effect would be a good future step in this line of research.

Third, several previous studies have demonstrated that artificial drainage increases streamflow in moderate sized (10^2-10^3 km^2) watersheds (Schottler et al., 2014; Foufoula-Georgiou et al., 2015). Though we cannot fully rule out the first and second mechanisms discussed above, artificial drainage for corn-soy agriculture affects substantial swaths of land in all study watersheds except the Chippewa, and has almost doubled in area in the MRB and IRB since 1940 according to the US Census of Agriculture reports. It is known ~~anecdotally~~ qualitatively that drainage has increased in density and efficiency during this same time. Using multiple lines of evidence from the analyses of very large basins and sub-basins it appears most likely that widespread agricultural drainage activities have amplified the streamflow response to relatively small changes in total precipitation. Frans et al. (2013) found that artificial drainage amplified annual runoff in the UMRB in some cases by as much as 40% locally. Improved information regarding the size, spacing, depth, and extent of artificial drainage would greatly enhance our ability to model agricultural systems and predict downstream impacts.

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Surface and subsurface drainage remains ~~an economically beneficial, yet~~ largely unregulated ~~land management practice in~~throughout the Midwestern USA and Canada ~~that affects enormous swaths of agricultural land~~ (Cortus et al., 2011). Drainage census data are prone to reporting inconsistencies and errors, overall underestimation of drainage from excluding farms less than 500 acres, and do not provide the information necessary for modeling basin hydrology in large agricultural watersheds (such as drain size, depth, spacing, and extent). However, these are the most comprehensive inventory of drainage in the United States. This raises the question: why is such a widespread practice with such potentially profound and pervasive impacts on watershed hydrology and water quality so poorly documented and regulated? Until we have the information necessary to calibrate and validate watershed models, it will be difficult to more precisely deconvolve proportional impacts of climate and artificial drainage on flows at large spatial scales.

Decreased residence time of water in the soil has substantially increased nutrient export from agricultural landscapes (Randall and Mulla, 2001; Kreiling and Houser, 2016; Schilling et al., 2017). Though artificial drainage reduces field erosion by reducing surface runoff, it has been shown to essentially have shifted the sediment source from fields to channels (Belmont, 2011; Belmont and Foufoula-Georgiou, 2017). ~~The cause of that shift is still linked to agricultural land use.~~ Basins experiencing increases in streamflow due to natural (climate) and anthropogenic (drainage) factors have increased stream power ~~and are expected therefore~~ available to erode and transport more sediments and sediment bound nutrients and contaminants. Improved ~~Future increases in precipitation are likely to further intensify the effects of artificial drainage. R~~runoff management, specifically increased residence time and damped peak flows, is most needed in spring and early summer when tiles are actively draining soils and precipitation events are large. Thus, substantial gains in water quality might only be achieved if some amount of the lost water storage capacity is reintroduced (e.g., wetlands, detention basins) into these agricultural watersheds.

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Acknowledgements

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Table 1. USGS stream gauging stations listed by study basin.

USGS gaging station	Station name	Period of record	Length (years)	Notes
Chippewa River ~~B~~basin (9 gauges)				
05356000	Chippewa River at Bishops Bridge, near Winter, WI	1929-2013	85	Mainstem river
05356500	Chippewa River near Bruce, WI	1929-2013	85	Mainstem river
05360500	Flambeau River near Bruce, WI	1952-2013	62	
05362000	Jump River at Sheldon, WI	1929-2013	85	
05365500	Chippewa River at Chippewa Falls, WI	1929-2013	81	Missing data: 1983 - 1986
05369000	Red Cedar River at Menomine, WI	1929-2013	85	
05368000	Hay River at Wheeler, WI	1951-2013	63	
05370000	Eau Galle River at Spring Valley, WI	1945-2013	69	
05369500	Chippewa River at Durand, WI	1929-2013	85	Mainstem river - Downstream gauge
Illinois River ~~B~~basin (20 gauges)				
05552500	Fox River at Dayton, IL	1929-2013	85	
05543500	Illinois River at Marseilles, IL	1929-2013	85	Mainstem river
05555300	Vermilion River near Leonore, IL	1932-2013	82	†
05556500	Big Bureau Creek at Princeton, IL	1937-2013	77	†
05554500	Vermilion River at Pontiac, IL	1943-2013	71	†
05569500	Spoon River at London Mills, IL	1943-2013	71	
05567500	Mackinaw River near Congerville, IL	1945-2013	69	†
05568500	Illinois River at Kingston Mines, IL	1940-2013	74	Mainstem river
05570000	Spoon River at Seville, IL	1929-2013	85	
05584500	La Moine River at Colmar, IL	1945-2013	69	
05585000	La Moine River at Ripley, IL	1929-2013	85	
05583000	Sangamon River Near Oakford, IL	1929-2013	79	Missing data: 1934 - 1939
05582000	Salt Creek near Greenview, IL	1942-2013	72	
05580000	Kickapoo Creek at Waynesville, IL	1948-2013	66	† *
05578500	Salt Creek near Rowell, IL	1943-2013	71	
05572000	Sangamon River at Monticello, IL	1929-2013	85	†
05576000	South Fork Sangamon River near Rochester, IL	1950-2013	64	
05577500	Spring Creek at Springfield, IL	1949-2013	65	†
05586100	Illinois River at Valley City, IL	1939-2013	75	Mainstem river - Downstream gauge
05587000	Macoupin Creek near Kane, IL	1929-2013	77	Missing data: 1933 - 1940

Minnesota River ~~B~~basin (12 gauges)				
05291000	Whetstone River near Big Stone City, SD	1932–2013	82	
05292000	Minnesota River at Ortonville, MN	1939–2013	75	Mainstem river
05304500	Chippewa River near Milan, MN	1938-2013	76	
05311000	Minnesota River at Montevideo, MN	1930-2013	84	Mainstem river
05313500	Yellow Medicine River near Granite Falls, MN	1940-2013	74	
05315000	Redwood River near Marshall, MN	1941-2013	73	
05316500	Redwood River near Redwood Falls, MN	1936-2013	78	
05317000	Cottonwood River near New Ulm, MN	1939-2013	75	
05320000	Blue Earth River near Rapidan, MN	1950-2013	64	
05320500	Le Sueur River near Rapidan, MN	1950-2013	64	
05325000	Minnesota River at Mankato, MN	1930-2013	84	Mainstem river
05330000	Minnesota River near Jordan, MN	1935-2013	79	Mainstem river - Downstream gauge
Red River of the North ~~B~~basin (22 gauges)				
05050000	Bois de Sioux River near White Rock, SD	1942-2013	72	
05046000	Otter Tail River near Fergus Falls, MN	1931-2013	83	
05051500	Red River of the North at Wahpeton, ND	1944-2013	70	Mainstem river
05053000	Wild Rice River near Abercrombie, ND	1933-2013	81	
05056000	Sheyenne River near Warwick, ND	1950-2013	64	
05057000	Sheyenne River near Cooperstown, ND	1945-2013	69	
05058000	Sheyenne River below Baldhill Dam, ND	1950-2013	64	
05059000	Sheyenne River near Kindred, ND	1950-2013	64	
05059500	Sheyenne River at West Fargo, ND	1930-2013	84	
05054000	Red River of the North at Fargo, ND	1929-2013	85	Mainstem river
05060500	Rush River at Amenia, ND	1947-2013	67	
05062000	Buffalo River near Dilworth, MN	1932-2013	82	
05066500	Goose River at Hillsboro, ND	1935-2013	79	
05064000	Wild Rice River at Hendrum, MN	1945-2013	67	Missing data: 1984 - 1985
05069000	Sand Hill River at Climax, MN	1947-2013	65	Missing data: 1984 - 1985
05074500	Red Lake River near Red Lake, MN	1934-2013	74	Missing data: 1994 - 1999
05075000	Red Lake River at High Landing near Goodridge, MN	1930-1999	70	Missing data: 2000 - 2013
05076000	Thief River near Thief River Falls, MN	1929-2013	83	Missing data: 1981 - 1982
05078000	Clearwater River at Plummer, MN	1940-2013	70	Missing data: 1979 - 1982
05078500	Clearwater River at Red Lake Falls, MN	1935-2013	77	Missing data: 1981 - 1982
05079000	Red Lake River at Crookston, MN	1929-2013	85	
05082500	Red River of the North at Grand Forks, ND	1929-2013	85	Mainstem river - Downstream gauge

† Tributary gauges, predominantly agricultural, not influenced by major dams
* Mean Annual Flow and Seven Day Low Flow Winter 1949-2013

Table 2. Site details for AmeriFlux sites used for comparison with Livneh et al. (2013) evapotranspiration data (L13), where L13(JJA) represents 17% reduction in ET during summer months June, July, and August.~~.~~ Average annual difference is positive when L13/L13(JJA) ET is greater than Ameriflux ET and negative when less than. Nearest study watersheds are abbreviated as follows: Chippewa River basin (CRB), Illinois River basin (IRB), Minnesota River basin (MRB), and Red River of the North basin (RRB).

Site name	**Willow Creek, WI**	**Bondville, IL**	**Rosemount, MN**	**Brookings, SD**
AmeriFlux site no.	US-WCr	US-Bo1	US-Ro1	US-Bkg
Latitude	45.8059	40.0062	44.7143	44.3453
Longitude	-90.0799	-88.2904	-93.0898	-96.8362
Nearest watershed[s]	CRB	IRB	MRB [CRB]	MRB [RRB]
Distance to nearest watershed (km)	0.463	13.049	43.807 [74.169]	25.949 [129.688]
Years	1999-2002	2003-2008	2004-2009	2004-2009
Vegetation	Deciduous broadleaf forest	Croplands	Croplands	Grasslands
Average difference L1~~4~~3-Ameriflux	+31%	+17%	+14%	-29%
Average difference L1~~4~~3(JJA)-Ameriflux	+19%	+7%	+5%	-34%

Table 3. Summary of the breakpoint years identified from land cover transition (LCT) (Fig. 3), piecewise linear regression (PwLR) of precipitation (P) and streamflow (Q), and continuous wavelet transform (CWT) of P and Q (Fig. 4).

	LCT (Fig. 3)	**P (PwLR)**	**Q (PwLR)**	**P (CWT, Fig. 4)**	**Q (CWT, Fig. 4)**
Red River of the North basin ~~RRB~~	2003/2004	1987/1988	1989/1990	No change	1995
Minnesota River basin~~MRB~~	1978/1979	1958/1959	1967/1968	No change	1980
Illinois River basin~~IRB~~	1961/1962	1981/1982	1981/1982	No change	1975
Chippewa River basin ~~CRB~~	2009/2010	1995/1996	1995/1996	No change	No change

Table 4. Observed average annual precipitation (P), flow (Q), evapotranspiration (ET) and storage $\left(\frac{dS}{dt}\right)$ depths (cm y^{-1}) for each basin during the pre-period (a) and post-period (b) split by 1974/1975 (1) and land cover transition (LCT) (2) breakpoints.

		Years	**P_{mean} (cm y^{-1})**	**Q_{mean} (cm y^{-1})**	**ET_{mean} (cm y^{-1})**	**$\frac{dS}{dt}_{mean}$ (cm y^{-1})**
Minnesota River basin~~B~~	1a	1935-1974	65.1	7.2	60.9	-3.0
	1b	1975-2011	70.0	13.4	64.2	-7.5
	2a	1935-1978	64.8	7.0	60.6	-2.8
	2b	1979-2011	71.0	14.4	65.0	-8.4
	1a†	1935-1974			55.6	2.3

	1b†	1975-2011			58.7	-2.0
	2a†	1935-1978			55.4	2.4
	2b†	1979-2011			59.3	-2.7
Red River of the North basin~~B~~	1a	1935-1974	53.4	3.7	45.1	4.7
	1b	1975-2011	57.7	6.7	47.4	3.5
	2a	1935-2003	54.5	4.6	45.6	4.4
	2b	2004-2011	63.3	10.1	51.6	1.5
	1a†	1935-1974			41.1	8.6
	1b†	1975-2011			43.3	7.6
	2a†	1935-2003			41.6	8.4
	2b†	2004-2011			47.4	5.8
Illinois River basin~~RB~~	1a	1939-1974	90.5	27.3	73.2	-10.0
	1b	1975-2011	95.2	33.0	75.1	-13.0
	2a	1939-1961	89.5	25.9	72.8	-9.3
	2b	1962-2011	94.4	32.2	74.8	-12.5
	1a†	1939-1974			66.9	-3.7
	1b†	1975-2011			68.7	-6.6
	2a†	1939-1961			66.5	-3.0
	2b†	1962-2011			68.4	-6.1
Chippewa River ~~B~~basin	1a	1935-1974	80.0	29.7	61.8	-11.5
	1b	1975-2011	82.1	29.8	62.7	-10.5
	2a	1935-2009	80.8	29.6	62.1	-11.0
	2b	2010-2011	88.4	33.3	68.5	-13.4
	1a†	1935-1974			56.5	-6.2
	1b†	1975-2011			57.4	-5.2
	2a†	1935-2009			56.8	-5.7
	2b†	2010-2011			62.3	-7.3

† 17% reduction in ET during summer months (JJA)

Supplement of

Human amplified changes in precipitation-runoff patterns in large river basins of the Midwestern United States

Sara A. Kelly et al.

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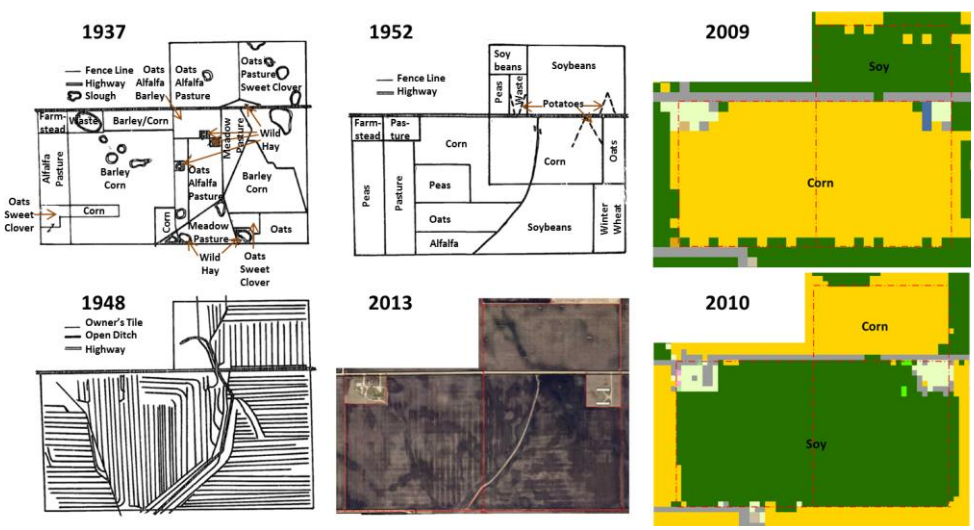

Figure S1: Field land use and tile arrangement before (1937) and after (1952) tile installation (1948) near Mapleton, MN (adapted from Burns, 1954); aerial photograph flown in spring 2013 shows the modern tile pattern remains relatively unchanged with a corn-soybean crop rotation (2009-2010), from the Cropland Data Layer (USDA NASS~~ational Agricultural Statistics Service Cropland Data Layer~~, 2013).

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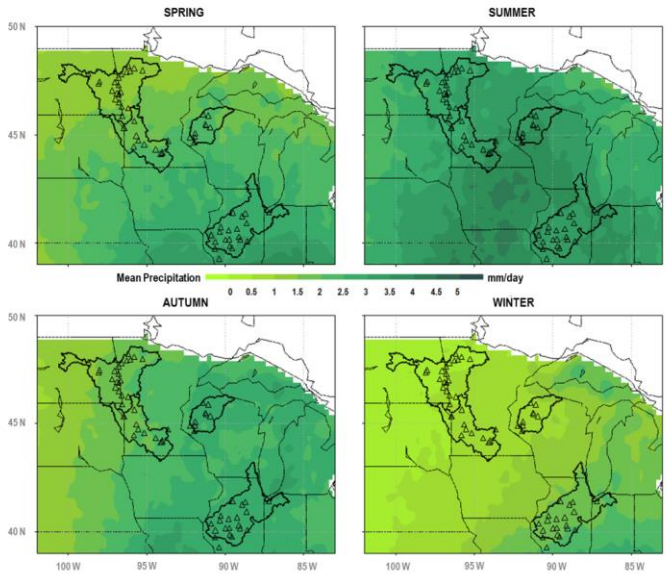

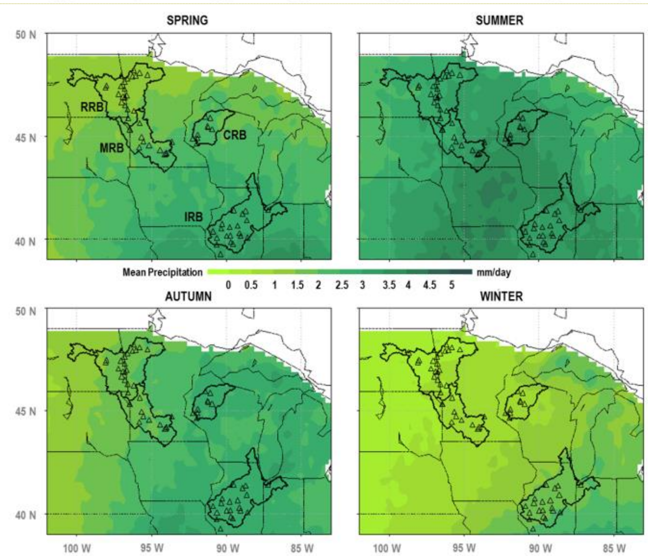

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Figure S2. Seasonally averaged long term daily Parameter elevation Regression on Independent Slopes Model (PRISM) precipitation means (1981-2010) across the Upper Midwest: spring (MAM), summer (JJA), autumn (SON), and winter (DJF); USGS gage locations for each study basin (Table 1) indicated by open triangles (PRISM Climate Group, 2004)**. Study basin acronyms are defined as: Red River of the North basin (RRB), Minnesota River basin (MRB), Chippewa River basin (CRB), and Illinois River basin (IRB).**

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Supplement of Section 3.2 - Climate records: precipitation and evapotranspiration

Comparison of monthly precipitation total reported as an average depth (cm) from Parameter elevation Regression on Independent Slopes Model (PRISM) ~~(~~, used in this study~~)~~, and Livneh et al. (2013) (L13) for each watershed is shown in ~~(~~Figure S3~~)~~. If PRISM and L13 precipitation depths were equivalent in every month, then all points would plot on the 1:1 line. On average (1935-2011) the difference between the two monthly precipitation datasets is 1% for each study watershed.

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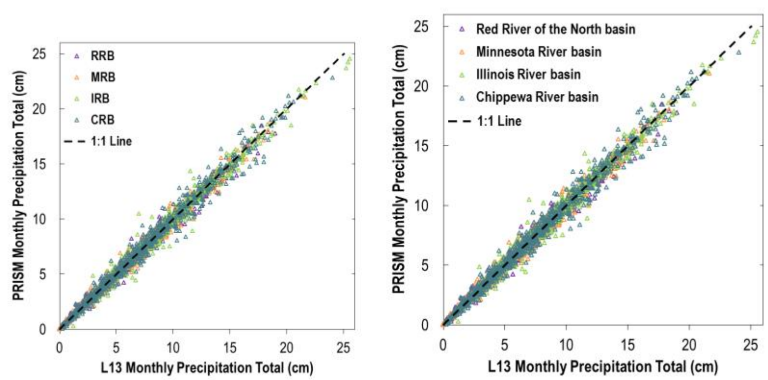

Figure S3. Spatially averaged, total monthly (cm) precipitation (1935-2011) for each watershed from Parameter elevation Regression on Independent Slopes Model ~~PRISM~~(PRISM Climate Group, 2004) **and Livneh et al. 2013 (L13) plotted with 1:1 line.**

Figure S4 shows a comparison of monthly (March-November during 2001-2011) ET_a estimates produced by Livneh et al. (2013) (L13) with ET_p estimates (available from: http://agwx.soils.wisc.edu/uwex_agwx/sun_water/et_wimn) produced following the methods of Diak et al. (1998) (D98) for a location in the Minnesota River basin~~B~~ (MRB), ~~(~~44 N, 94 W~~)~~ and the Chippewa River ~~B~~basin (CRB), ~~(~~45.2 N, 91.6 W~~)~~. On average, the estimates of ET_a are 19% (raw) and 26% (17% reduction in JJA ET_a) lower than estimates of ET_p in the MRB, and 16% (raw) and 24% (17% reduction in JJA ET_a) lower than estimates of ET_p in the CRB.

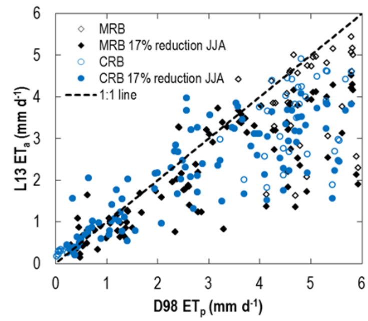

Figure S4. Monthly (March-November) average daily (mm d^{-1}) estimates of ET$_p$ following methods of Diak et al., 1998 (D98) versus estimates of ET$_a$ from Livneh et al., 2013 (L13) during 2001-2011.

Figure S5 shows average monthly ET$_a$ from Livneh et al. (2013) compared against four AmeriFlux sites near the study watersheds (Table 2) as well as data from Bryan et al. (2015). In general, the L13 data show an earlier peak in ET$_a$ for the cropland sites in Rosemount, MN and Bondville, IL, and overestimate average annual ET$_a$ by 17% (raw) and 7% (17% reduction in JJA) for Bondville and 14% (raw) and 5% (17% reduction in JJA) for Rosemount. The L13 data overestimate ET$_a$ at Willow Creek, WI (broadleaf deciduous forest) by as much as 31% (raw) and 19% (17% reduction in JJA) annually, and underestimate ET$_a$ at Brookings, SD (grassland) by 29% (raw) and 34% (17% reduction in JJA) annually.

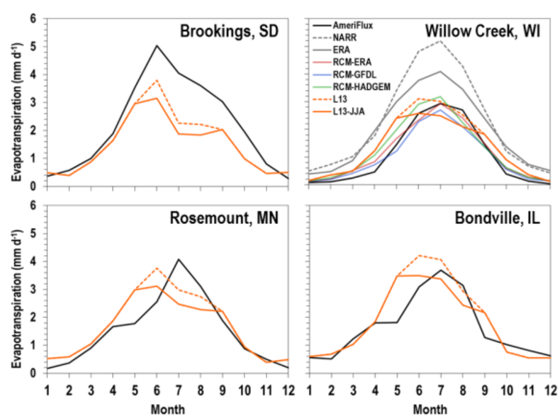

Figure S5. Average monthly evapotranspiration rate (mm d^{-1}) at four AmeriFlux sites (see Table 2) compared to modeled evapotranspiration rates used in this study (L13 & L13-JJA) and Bryan et al. 2015.

The L13 ET$_a$ estimates were calculated in VIC using the Hansen et al. (2000) static global vegetation classification, and did not consider artificial drainage. Therefore, the dominant mechanism for losing soil water in May and June is expected to be through ET$_a$ loss according to the L13 estimates. In contrast, ET$_a$ losses in May and June at Ameriflux sites are relatively low since crops are absent or very young and soil water likely drains primarily via artificial drainage. We expect that the effects of drainage influence ET_a during the peak growing season as well. Because drainage improves crop growing conditions early in the growing season, late growing season ET_a may be higher in drained fields than undrained fields. This would be an interesting further line of study. Regardless, it seems reasonable that the L13 ET_a estimates would seasonally mismatch the Rosemount and Bondville Ameriflux station ET_a estimates, given the presence/absence of artificial drainage.

ET_a estimates may dramatically underestimate Ameriflux ET_a estimates in Brookings, SD due to differences in crop coefficients or misclassification of grasslands and croplands; corn has been found to have lower ET_a rates than some grasses (Hickman et al., 2010). Due to the coarse resolution of the global vegetation input for the L13 VIC model, parts of southern Wisconsin appear to be misclassified as broadleaf deciduous forest instead of cropland. Some studies in the Great Lakes region report broadleaf deciduous forest to have slightly higher annual ET_a rates than cropland (Mao and Cherkauer, 2009; Mishra et al., 2010). Likely of larger significance is that Livneh et al. (2013) and Maurer et al. (2002) do not suggest that they considered lake and wetland effects on evapotranspiration, which in the Great Lakes region can be significant (Bryan et al., 2015). Furthermore, the Hansen et al. (2000) global vegetation classification masks bodies of water, as the land cover input.

The fact that the L13 ET_a estimates mismatch Ameriflux estimates seasonally provides assurance that the L13 ET_a estimates are appropriate for testing our hypothesis. The lack of artificial drainage is what allows us to test whether factors beyond climate contribute to modern streamflow increases in the Midwestern US.

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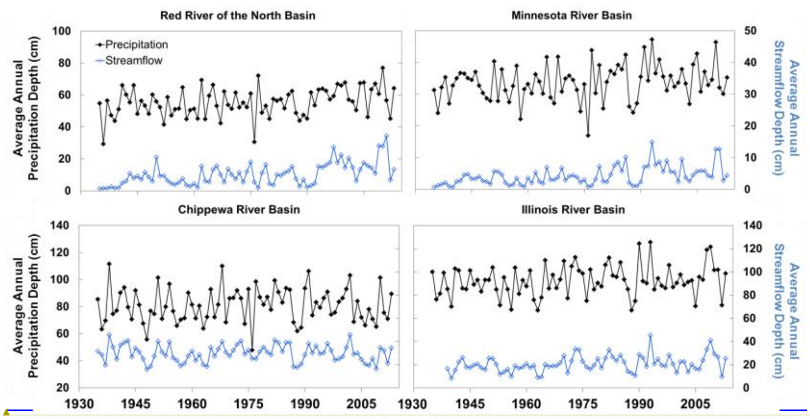

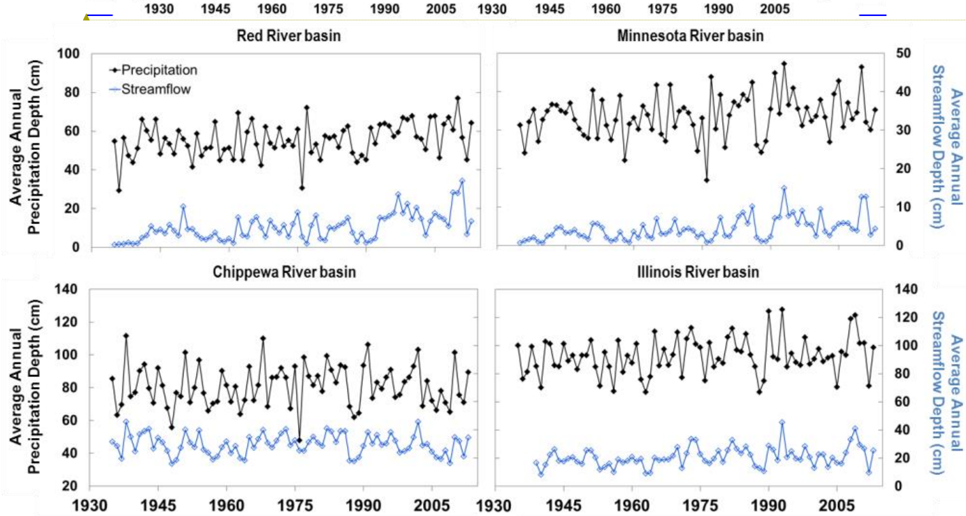

Figure S6. Annual, spatially averaged watershed precipitation and streamflow depths (cm) for each study basin.

Table S1. Resulting p-values of 624~~572~~ statistical tests (t-test and Kolmogorov–Smirnov [KS]-test) comparing pre-period and post-period flow and precipitation based on the 1974/1975, piecewise linear regression (PwLR), and land cover transition (LCT) breakpoints for each basin (Table 3). P-values are highlighted based on their significance: bolded values are p-values with 95% confidence level or greater, grey values are p-values with less than a 95% confidence level, and black values are p-values where significance depends on the breakpoint. Italicized grey values reported for the CRB are not reliable because the post-period includes fewer than 10 years of data.

Flow: t-test			Flow: KS-test			Precipitation: t-test			Precipitation: KS-test		
74/75	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**	**74/75**	**PwLR**	**LCT**

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Chippewa River basin~~RB~~	January	0.341	0.893	0.846	0.653	0.958	0.902	0.278	0.097	0.214	0.223	0.050	0.082
	February	0.372	0.680	0.851	0.449	0.878	0.953	0.337	0.039	0.309	0.446	0.071	0.367
	March	0.566	0.871	0.525	0.219	0.749	0.205	0.188	0.369	0.574	0.234	0.348	0.700
	April	0.468	0.267	0.719	0.506	0.152	0.416	0.192	0.277	0.258	0.169	0.308	0.575
	May	0.826	0.485	0.264	0.482	0.311	0.622	0.933	0.374	0.187	0.906	0.697	0.445
	June	0.900	0.552	0.211	0.908	0.628	0.142	0.833	0.434	0.117	0.945	0.587	0.246
	July	0.706	0.775	0.308	0.584	0.893	0.606	0.463	0.609	0.358	0.567	0.794	0.360
	August	0.174	0.508	0.364	0.354	0.450	0.200	0.496	0.945	0.769	0.760	1.000	0.856
	September	0.517	0.990	0.723	0.357	0.958	0.654	0.286	0.912	0.752	0.657	0.925	0.654
	October	0.103	0.778	0.593	0.110	0.887	0.817	**0.022**	**0.026**	0.304	0.097	0.073	0.423
	November	0.240	0.894	0.713	0.337	0.887	0.902	0.510	0.905	0.806	0.375	0.944	0.874
	December	0.263	0.973	0.806	0.387	0.971	0.931	0.380	0.135	0.062	0.337	0.175	0.045
	Annual	0.499	0.793	0.340	0.721	0.918	0.291	0.243	0.571	0.295	0.246	0.764	0.614
Illinois River basin~~B~~	January	0.123	0.030	0.092	0.136	0.079	0.265	0.543	0.250	0.529	0.454	0.425	0.211
	February	0.355	0.082	0.184	0.353	0.043	0.216	0.224	0.108	0.764	0.433	0.359	0.899
	March	0.035	0.062	0.045	0.104	0.114	0.099	0.649	0.777	0.619	0.619	0.836	0.828
	April	0.174	0.438	0.158	0.335	0.479	0.353	0.780	0.832	0.588	0.883	0.947	0.638
	May	0.182	0.344	0.155	0.126	0.398	0.161	0.212	0.113	0.326	0.063	0.063	0.138
	June	0.105	0.077	0.280	0.082	0.071	0.117	0.798	0.742	0.845	0.811	0.643	0.954
	July	0.451	0.411	0.525	0.518	0.436	0.614	0.453	0.585	0.214	0.585	0.519	0.443
	August	0.090	0.249	0.212	0.181	0.508	0.259	0.054	0.408	0.257	0.037	0.475	0.108
	September	0.004	0.062	0.009	0.003	0.111	0.041	0.511	0.465	0.118	0.685	0.728	0.113
	October	0.074	0.147	0.065	0.082	0.139	0.142	0.142	0.072	0.363	0.113	0.143	0.378
	November	**0.034**	**0.007**	**0.041**	0.075	0.008	0.074	0.023	0.004	0.109	0.053	0.013	0.045
	December	**0.021**	**0.011**	**0.010**	**0.040**	**0.019**	**0.022**	0.122	0.081	0.039	0.136	0.203	0.050
	Annual	**0.011**	**0.019**	**0.017**	**0.012**	**0.018**	**0.020**	0.086	0.075	0.085	0.117	0.141	0.183
Minnesota River ~~B~~basin	January	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**	0.096	0.520	0.182	0.369	0.672	0.338
	February	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	0.722	0.842	0.659	0.540	0.938	0.604
	March	**0.007**	**0.005**	**0.002**	0.089	0.055	0.074	0.017	0.394	0.060	0.107	0.515	0.148
	April	**0.041**	**0.039**	**0.016**	**0.011**	**0.034**	**0.003**	0.159	0.164	0.239	0.489	0.344	0.684
	May	**0.000**	**0.001**	**0.000**	**0.001**	**0.001**	**0.001**	0.716	0.366	0.469	0.807	0.657	0.636
	June	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.500	0.957	0.418	0.807	0.879	0.677
	July	**0.002**	**0.007**	**0.000**	**0.021**	**0.020**	**0.003**	0.300	0.107	0.151	0.351	0.230	0.223
	August	**0.008**	**0.012**	**0.000**	**0.017**	**0.040**	**0.001**	0.239	0.641	0.133	0.097	0.806	0.064
	September	0.017	0.062	0.001	0.106	0.225	0.015	0.224	0.077	0.242	0.334	0.112	0.261
	October	**0.002**	**0.001**	**0.000**	**0.012**	**0.007**	**0.002**	0.082	0.015	0.029	0.115	0.088	0.116
	November	**0.001**	**0.000**	**0.000**	**0.006**	**0.000**	**0.001**	0.262	0.418	0.380	0.260	0.519	0.445

	December	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	0.435	0.138	0.385	0.608	0.457	0.413
	Annual	**0.000**	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	0.033	0.072	0.011	0.098	0.199	0.051
Red River of the North basin ~~RRB~~	January	**0.000**	**0.000**	**0.005**	**0.005**	**0.000**	**0.013**	0.117	0.169	0.412	0.112	0.105	0.368
	February	**0.000**	**0.000**	**0.016**	**0.003**	**0.000**	**0.034**	0.155	0.321	0.050	0.246	0.326	0.183
	March	0.006	0.012	0.171	0.011	0.005	0.217	0.050	0.108	0.021	0.062	0.247	0.054
	April	0.069	0.079	0.036	0.105	0.102	0.115	0.981	0.902	0.619	0.974	0.823	0.574
	May	**0.016**	**0.003**	**0.004**	0.059	0.013	0.014	0.321	0.039	0.046	0.312	0.129	0.186
	June	**0.015**	**0.000**	**0.001**	**0.038**	**0.002**	**0.001**	0.170	0.138	0.351	0.105	0.032	0.569
	July	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	**0.005**	0.288	0.251	0.886	0.244	0.418	0.943
	August	**0.000**	**0.000**	**0.013**	**0.000**	**0.000**	**0.043**	0.687	0.551	0.681	0.598	0.650	0.786
	September	**0.002**	**0.000**	**0.024**	0.002	0.000	0.084	0.094	0.036	0.047	0.009	0.013	0.081
	October	**0.003**	**0.000**	**0.010**	0.003	0.002	0.053	**0.010**	**0.015**	**0.002**	**0.011**	**0.003**	**0.004**
	November	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**	**0.003**	0.409	0.560	0.918	0.270	0.341	0.943
	December	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.013**	0.487	0.058	0.000	0.639	0.071	0.002
	Annual	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.005**	**0.019**	**0.004**	**0.009**	**0.010**	**0.008**	**0.027**

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Section 3. Summary of Major Manuscript Changes based on Referee Comments

- Provided further discussion of Livneh ET estimates and our rationale for selecting these data over other data.
- Provided rationale for focusing on drainage effects on streamflows and sediment, and acknowledged literature related to agricultural drainage and nutrients.
- Added brief description of study watershed soils.
- Removed equation 2 and shortened wavelet methods in section 3.4.
- Shortened section 4.1
- Compared results to similar studies in the literature (e.g. Xu et al. 2013, Frans et al. 2013, Schottler et al. 2014) and expanded discussion of the role of ET changes in the water budget.
- Addressed minor referee comments and made edits to figures, captions, abbreviations, word use, etc.