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Interactive comment on “Stream restoration and sanitary infrastructure alter sources and fluxes of water, carbon, and nutrients in urban watersheds”

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To the Editor of HESS:

We would like to thank the editor and reviewers for all of their comments and suggestion. We have compiled the editor's and both of the reviewer's comments below and we have thoroughly addressed and responded to each comment. Please note that all

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of our responses are in red.

Thank you, Michael Pennino

Response to Referee 2 Comments

The topic of how urban streams transfer nutrients is of interest. The experimental setup is quite confusing though, it is not obvious why and what you compare. As suggested by reviewer 1, we have now changed some of the confusing terminology and simplified the abstract, introduction, and the methods. We believe we have made the experimental set up more clear and easy to understand. For example, 1) we are now primarily using the terms restored or urban degraded streams, 2) we clarified the introduction where we list our objectives and we make our second objective more clear (as described above) by stating that we are looking at hydrology and nutrient sources in 1 restored and 3 urban degraded streams “to assess the role of stream restoration and potential pollutant sources, such as leaky sanitary sewers,” 3) we simplified our site description section (described more below), and 4) we simplified the methods section on “Comparison of Pre and Post Restoration Hydrologic Response” by putting most of the text in to Supplementary Material.

Some terminology is not very specific and confusing: unrestored, sanitary infrastructure etc. How are you assessing the impact of the ‘sanitary infrastructure’? We are no longer using the term “unrestored”, instead we are using “urban degraded streams.” We are also no longer using “sanitary infrastructure” but instead “sewers” or “sewer infrastructure.”

To assess the impact of sewer infrastructure (also described elsewhere) we used data on carbon quality (fluorescence spectroscopy results), data on ¹⁵N-nitrate stable isotopes, data on fluoride and iodide concentrations, and carbon and nitrogen export results.

Do you have enough study sites to derive meaningful and statistically significant con-

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clusions? Similar to our response to the first reviewer, we can say based on our statistical analysis of time series data collected at each of the four sites whether one stream has different hydrologic metrics, nutrient sources, or exports than the other sites. However, because we do not have enough replication of study sites, we cannot say with statistical confidence whether stream restoration or management has a significant effect (except for the before and after hydrologic analysis for the restored stream site). Yet, based on the results of this study we can still suggest the potential influence of leaky sewer infrastructure and stream restoration. Our results also provide new information regarding sources and exports of water, carbon, and nitrogen in urban restored streams, and there are relatively few papers analyzing sources of water, carbon, and nitrogen in urban restored and degraded streams.

In my opinion, lots of the comparison between streams/catchments in terms of the 'sanitary infrastructure' is speculative and does not support your conclusions. We feel that our revisions and the literature added support our conclusions. There has been considerable background work evaluating the importance of leaky sewers in these watersheds. Please see our more detailed and specific responses below.

Below are some more specific comments:

Title – should be fluxes of water and nutrients We do not agree with this change because carbon is not typically considered a nutrient and we want to make sure it is clear that carbon is studied in this paper.

Abstract – please rewrite confusing parts: 'more similar to a less developed', 'higher and less frequent streamflow' We changed 'more similar to a less developed' to 'more similar to a stream with stormwater management systems and less impervious surface cover in its watershed.'

We changed 'higher and less frequent streamflow' to just 'higher streamflow.'

Abstract – please rewrite 'stream draining stormwater management' We changed this

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to 'a stream with stormwater management systems . . . in its watershed.'

Abstract – please rewrite 'Although stream restoration appeared to potentially influence hydrology to some degree,' – did it or did it not? We removed this part of the sentence because it was unnecessary and the question was already answered previously in the abstract.

Abstract – please choose groundwater or ground water We went through the abstract and whole manuscript to make sure to consistently use 'groundwater.'

Abstract and introduction – the description of what streams you measure is very confusing, do you measure only urban streams? Restored and unrestored? Please rewrite to make it clear what you compare with what. The abstract and introduction have been revised to make it clear that we are measuring only urban streams. We removed the use of the term unrestored and used the term "urban degraded streams" instead.

Methods, page 13154, line 9 – please rewrite 'the entire mainstem of the stream from headwaters to mouth is greater than 95% restored' We made this part a new sentence and changed it to read "Also, about 95% of Minebank Run's mainstem has been restored . . ."

Methods, page 13154, most of this information should be in a table This information is in Table 1. We have removed some of the text from this paragraph on page 13154 and summarized some of the data for the four sites.

Methods, page 13155, please consider putting some of this text in supplementary material Most of these methods from this section "Comparison of pre and post restoration hydrologic response" were moved to supplementary material and some of the text was re-written for clarity.

Methods, page 13157 – how long were the NO3N samples stored for before analysis? In the supplementary material we wrote "All nitrogen species, except samples for stable isotope analysis, were preserved by acidifying to pH 2 with sulfuric acid and stored

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frozen in HDPE bottles until analysis." And "All other samples, besides NO₃- isotopes samples, were analyzed within 1-2 months."

For nitrate isotopes we added this text to the supplementary material: "Samples for nitrate isotope analysis were all analyzed on the same date, resulting in the samples being stored frozen from 7 months to 2 years and 7 months." We could not find any literature to suggest there is any difference in isotope results depending on storage time.

Methods section is far too long, please make it more concise. We have considerably cut down the site description section and the section "Comparison of pre and post restoration hydrologic response." We feel that the rest of the methods section material is necessary.

Methods - I am not sure how useful are your load estimates if the approach does not sample highflows? Even though the annual loads may not fully estimate stormflow contribution, we added text to say "...because all four sites are within the same city and receive relatively the same rainfall during storm events, the relative annual loads estimated for the sites are comparable and it is appropriate to draw conclusions among the four study sites."

Discussion: A lots of discussion is speculative. Do you have any evidence in support of your hypotheses about leaky sewers, erosion of stream channel etc? There are several sources of evidence to suggest that there are leaky sewers at the streams in this study, which were stated in the results and discussion (but we have now added any new references and added more discussion to the text):

1) The high 15N-NO₃ isotope levels and the nitrate isotope mixing model results suggests N wastewater sources at all four sites (Kaushal et al., 2011, Divers et al. 2014). Also during summer baseflow, the 15N-NO₃- isotope levels were consistently high along the entire stream length at all four sites, also suggesting the influence of leaky sewers inputs through groundwater recharge (Divers et al. 2014, Hall et al. 2016).

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2) The fluorescence spectroscopy results indicates there is more labile organic matter and protein-like organic matter in the urban degraded streams as well as the restored stream, suggesting wastewater sources (leaky sewers, since there are no point wastewater discharges) based on the literature (Baker, 2001; Goldman et al., 2012; Li et al., 2015; Yu et al., 2015).

3) Evidence from iodide and fluoride support leaky sewer pipes (Kaushal et al., 2014, Darcan et al., 2005; Gehr and Leduc, 1992; Xu et al., 2016), because fluoride is applied as an additive to drinking water (Dean et al., 1950) and iodide is used in table salt (Waszkowiak and Szymandera-Buszka, 2008).

4) We also added more introductory text on how leaky sewers are a global problem with references from the United States, Europe and Asia: “These techniques and others have been used globally to detect the influence of leaky sewer infrastructure on water quality (Ekklesia et al., 2015; Hall et al., 2016; Risch et al., 2015; Tran et al., 2014; Wolf et al., 2012) and it has been shown that sewer leaks have impacts during baseflow and stormflow (Divers et al., 2013; Divers et al., 2014; Phillips and Chalmers, 2009; Rose, 2007).”

5) The increase in wastewater inputs from wastewater sources (which include C, N, and P) during stormflow (pulsed behavior) has been shown to be related to leaky pipes and sewer overflows (Divers et al., 2014; Phillips and Chalmers, 2009; Kaushal et al., 2011).

6) We have added text saying that “In fact, Baltimore City has detailed records for the dates and locations of sewer overflows through their open data website (data.baltimorecity.gov) and these sewer overflows have occurred within the watersheds in this study.”

In terms of evidence for erosion of the stream channel, we indicated that this was observed by the authors in the test by stating “(personal observation).”

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The following are citations for the references listed above in response to this question:

Baker, A.: Fluorescence excitation-emission matrix characterization of some sewage-impacted rivers, *Environ. Sci. Technol.*, 35, 948-953, 2001.

Darcan, S., Unak, P., Yalman, O., Lambrecht, F. Y., Biber, F. Z., Goksen, D., and Coker, M.: Determination of iodine concentration in urine by isotope dilution analysis and thyroid volume of school children in the west coast of Turkey after mandatory salt iodization, *Clinical Endocrinology*, 63, 543-548, 2005.

Dean, H. T., Arnold, F. A., Jay, P., and Knutson, J. W.: Studies on mass control of dental caries through fluoridation of the public water supply, *Public Health Reports*, 65, 1403-1408, 1950.

Divers, M. T., Elliott, E. M., and Bain, D. J.: Constraining Nitrogen Inputs to Urban Streams from Leaking Sewers Using Inverse Modeling: Implications for Dissolved Inorganic Nitrogen (DIN) Retention in Urban Environments, *Environ. Sci. Technol.*, 47, 1816-1823, 2013.

Divers, M. T., Elliott, E. M., and Bain, D. J.: Quantification of Nitrate Sources to an Urban Stream Using Dual Nitrate Isotopes, *Environ. Sci. Technol.*, 48, 10580-10587, 2014.

Ekklesia, E., Shanahan, P., Chua, L. H. C., and Eikaas, H. S.: Temporal variation of faecal indicator bacteria in tropical urban storm drains, *Water Res.*, 68, 171-181, 2015.

Gehr, R. and Leduc, R.: ASSESSING EFFLUENT FLUORIDE CONCENTRATIONS FOLLOWING PHYSICOCHEMICAL WASTE-WATER TREATMENT, *Canadian Journal of Civil Engineering*, 19, 649-659, 1992.

Goldman, J. H., Rounds, S. A., and Needoba, J. A.: Applications of Fluorescence Spectroscopy for Predicting Percent Wastewater in an Urban Stream, *Environ. Sci. Technol.*, 46, 4374-4381, 2012.

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Hall, S. J., Weintraub, S. R., Eriksson, D., Brooks, P. D., Baker, M. A., Bowen, G. J., and Bowling, D. R.: Stream Nitrogen Inputs Reflect Groundwater Across a Snowmelt-Dominated Montane to Urban Watershed, *Environ. Sci. Technol.*, 50, 1137-1146, 2016.

Kaushal, S. S., Groffman, P. M., Band, L. E., Elliott, E. M., Shields, C. A., and Kendall, C.: Tracking Nonpoint Source Nitrogen Pollution in Human-Impacted Watersheds, *Environ. Sci. Technol.*, 45, 8225-8232, 2011.

Kaushal, S. S., Delaney-Newcomb, K., Findlay, S. E. G., Newcomer, T. A., Duan, S., Pennino, M. J., Sivirichi, G. M., Sides-Raley, A. M., Walbridge, M. R., and Belt, K. T.: Longitudinal patterns in carbon and nitrogen fluxes and stream metabolism along an urban watershed continuum, *Biogeochemistry*, DOI 10.1007/s10533-014-9979-9, 2014.

Li, W. H., Liu, Y. X., Wang, W., Sheng, G. P., Yu, H. Q., and Shuai, L.: Analysis of Samples from Wastewater Treatment Plant and Receiving Waters Using EEM Fluorescence Spectroscopy, Spectroscopy and Spectral Analysis, 35, 940-945, 2015.

Phillips, P. and Chalmers, A.: WASTEWATER EFFLUENT, COMBINED SEWER OVERFLOWS, AND OTHER SOURCES OF ORGANIC COMPOUNDS TO LAKE CHAMPLAIN, *Journal of the American Water Resources Association*, 45, 45-57, 2009.

Risch, E., Gutierrez, O., Roux, P., Boutin, C., and Corominas, L.: Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems, *Water Res.*, 77, 35-48, 2015.

Rose, S.: The effects of urbanization on the hydrochemistry of base flow within the Chattahoochee River Basin (Georgia, USA), *Journal of Hydrology*, 341, 42-54, 2007.

Tran, N. H., Hu, J. Y., Li, J. H., and Ong, S. L.: Suitability of artificial sweeteners as indicators of raw wastewater contamination in surface water and groundwater, *Water Res.*, 48, 443-456, 2014.

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Waszkowiak, K. and Szymandera-Buszka, K.: Effect of storage conditions on potassium iodide stability in iodised table salt and collagen preparations, International Journal of Food Science and Technology, 43, 895-899, 2008.

Wolf, L., Zwiener, C., and Zemann, M.: Tracking artificial sweeteners and pharmaceuticals introduced into urban groundwater by leaking sewer networks, Science of the Total Environment, 430, 8-19, 2012.

Xu, Z. X., Wang, L. L., Yin, H. L., Li, H. Z., and Schwegler, B. R.: Source apportionment of non-storm water entries into storm drains using marker species: Modeling approach and verification, Ecological Indicators, 61, 546-557, 2016.

Yu, H. B., Song, Y. H., Gao, H. J., Liu, L., Yao, L. L., and Peng, J. F.: Applying fluorescence spectroscopy and multivariable analysis to characterize structural composition of dissolved organic matter and its correlation with water quality in an urban river, Environmental Earth Sciences, 73, 5163-5171, 2015.

The hydrological metrics and their interpretation is convincing but not the biogeochemical part of the study. Perhaps you should tease out more the differences in nutrients. At the moment this aspect is not clear. We added to the discussion section on nutrient sources and exports further interpretations for why the restored stream sometimes behaved differently than the other streams.

1) Specifically, we added details to the discussion on nitrate sources to show the influence of leaky sewers, seasons, and differences in sites: "High $^{15}\text{N-NO}_3^-$ isotope levels are indicative of nitrate from wastewater sources (Divers et al., 2014; Kaushal et al., 2011). . . . Due to stream restoration at MBR, the neighboring sewer pipes were repaired and stabilized (Doheny et al., 2006; Mayer et al., 2010; US EPA, 2009), likely resulting in less sewer leaks at Minbank Run in and along the restored reach. During summer baseflow, the $^{15}\text{N-NO}_3^-$ isotope levels were consistently high along each stream length suggesting the influence of leaky sewers inputs through groundwater recharge (Divers et al., 2014; Hall et al., 2016), but during the rainier spring season,

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the more urban streams (DRN and PMR) showed a decline in ^{15}N -NO₃- isotope levels indicating possible dilution of sewer sourced nitrate from rainwater entering from connected impervious surfaces (Divers et al., 2014). This dilution of wastewater NO₃- was not observed at the other sites, potentially due to less connected impervious surfaces at the least urban watershed (RRN) and the reduction of peak discharge due to the reconnected floodplain for the restored stream (MBR) (Boyer and Kieser, 2012; Cendon et al., 2010; Poff et al., 2006).

2) In the section on C sources we provide further references on why the fluorescence results suggest C sources from wastewater: “From studies throughout the globe, it is known that protein-like and more bioavailable or labile organic matter is typically associated with wastewater carbon sources (Baker, 2001; Goldman et al., 2012; Li et al., 2015; Yu et al., 2015).” “As a result, the higher BIX, P/H ratio, and protein-like organic matter in the restored stream MBR, as well as the more urban watersheds (PMR and DRN), is likely due to leaky sewers typically found in older urban watersheds (Hudson et al., 2008; Kaushal et al., 2011) since the watersheds in this study are not influenced by combined sewer overflows or typical point source discharges of wastewater.”

3) In the section on C exports we provided further interpretation on why the restored stream had the lowest C exports. “The restored stream also likely had lower C exports due to increased ability to retain and process carbon in transient storage zones, such as pools, in the reconnected floodplain or through hyperheic exchange (Bukaveckas, 2007; Groffman et al., 2005; Mulholland et al., 1997; Pennino et al., 2014), whereas degraded urban streams that are highly eroded can have less transient storage areas to potentially store and process carbon (Kurth et al., 2015; Sudduth et al., 2011a).”

4) We added more interpretation for why the N and P exports were lower for the restored stream. “The higher TN exports in the more urban sites (PMR and DRN) compared to the restored stream (MBR) may be due to various reasons, such as greater N inputs from leaky sewers in the more urban and older watersheds and/or greater N removal through denitrification in the restored stream due its hydrologically connected

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floodplains (Kaushal et al., 2008), and alluvial wetlands, and greater hyporheic exchange (Bukaveckas, 2007; Harrison et al., 2011; Kaushal et al., 2008; Roley et al., 2012). In fact, the stream restoration at MBR involved some repairs to help stabilize the sewer pipes (Doheny et al., 2006; Mayer et al., 2010; US EPA, 2009) and consequently may have reduced sewer leaks, but detailed research is needed to evaluate the effects of sewer repairs on watershed N inputs.”

For Phosphorus we added “The lower TP exports in the restored stream may be due to increased hyporeic exchange and floodplain connection, which have been shown to increase P retention (Butturini and Sabater, 1999; Mulholland et al., 1997).”

5) We also added to the interpretation on why the restored stream had less pulsed C and nutrient exports and less exports during higher flows. “The lower proportion of N exports during higher flows for the restored stream (MBR) may be due to the connected floodplain attenuating higher flows, as evidenced by the effective discharge results described above and due to less connected impervious cover (Poff et al., 2006; Smith et al., 2013).” Later in the discussion we added: “The higher C, N, and P exports during baseflow at the restored stream (MBR) and the least urban stream likely corresponds with there being greater groundwater recharge at these sites, due to less impervious surface cover and floodplain reconnection (Boyer and Kieser, 2012; Cendon et al., 2010).”

To the following sentence we added new citations: “Dissolved C, N, P, F-, and I- exports in the more urban watersheds could have also been more variable due to runoff from impervious surfaces and/or increased contributions from storm drains (Bernhardt et al., 2008; Hatt et al., 2004) and elsewhere in the stream corridor (i.e. sewage leaks) during storms, as shown in other studies (Divers et al., 2014; Kaushal et al., 2011; Phillips and Chalmers, 2009).”

We also added this sentence: “The attenuation of peak discharge due to stream restoration observed at MBR, which reconnected the stream with the floodplain is likely

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a large factor in why MBR had comparatively less pulses in C and nutrient exports. Also, the stabilization and replacement of sewer pipes along the restored stream (Doheny et al., 2006; Mayer et al., 2010; US EPA, 2009) likely reduced the potential for C and nutrients to leak into the restored stream.”

The following are citations for the references listed above in response to this question:

Bernhardt, E. S., Band, L. E., Walsh, C. J., and Berke, P. E.: Understanding, managing, and minimizing urban impacts on surface water nitrogen loading, *Year in Ecology and Conservation Biology* 2008, 1134, 61-96, 2008.

Boyer, K. B. and Kieser, M. S.: URBAN STORMWATER MANGEMENT-AN MS4 SUCCESSION STORY FOR WESTERN MICHIGAN UNIVERSITY, *Journal of Green Building*, 7, 28-39, 2012.

Bukaveckas, P. A.: Effects of channel restoration on water velocity, transient storage, and nutrient uptake in a channelized stream, *Environ. Sci. Technol.*, 41, 1570-1576, 2007.

Butturini, A. and Sabater, F.: Importance of transient storage zones for ammonium and phosphate retention in a sandy-bottom Mediterranean stream, *Freshwater Biology*, 41, 593-603, 1999.

Cendon, D. I., Larsen, J. R., Jones, B. G., Nanson, G. C., Rickleman, D., Hankin, S. I., Pueyo, J. J., and Maroulis, J.: Freshwater recharge into a shallow saline groundwater system, Cooper Creek floodplain, Queensland, Australia, *Journal of Hydrology*, 392, 150-163, 2010.

Doheny, E. J., Starsoneck, R. J., Striz, E. A., and Mayer., P. M.: Watershed characteristics and pre-restoration surface-water hydrology of Minebank Run, Baltimore County, Maryland, water years 2002–04. USGS Scientific Investigations Rep. 2006–5179. USGS, Reston, VA, 2006. 2006.

Groffman, P. M., Dorsey, A. M., and Mayer, P. M.: N processing within geomorphic
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structures in urban streams, *Journal of the North American Benthological Society*, 24, 613-625, 2005.

Harrison, M. D., Groffman, P. M., Mayer, P. M., Kaushal, S. S., and Newcomer, T. A.: Denitrification in Alluvial Wetlands in an Urban Landscape, *Journal of Environmental Quality*, 40, 634-646, 2011.

Hatt, B. E., Fletcher, T. D., Walsh, C. J., and Taylor, S. L.: The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams, *Environ. Manage.*, 34, 112-124, 2004.

Hudson, N., Baker, A., Ward, D., Reynolds, D. M., Brunsdon, C., Carliell-Marquet, C., and Browning, S.: Can fluorescence spectrometry be used as a surrogate for the Biochemical Oxygen Demand (BOD) test in water quality assessment? An example from South West England, *Science of the Total Environment*, 391, 149-158, 2008.

Kaushal, S. S., Groffman, P. M., Mayer, P. M., Striz, E., and Gold, A. J.: Effects of stream restoration on denitrification in an urbanizing watershed, *Ecological Applications*, 18, 789-804, 2008.

Kurth, A. M., Weber, C., and Schirmer, M.: How effective is river restoration in re-establishing groundwater-surface water interactions? - A case study, *Hydrology and Earth System Sciences*, 19, 2663-2672, 2015.

Mayer, P. M., Groffman, P. M., Striz, E. A., and Kaushal, S. S.: Nitrogen Dynamics at the Groundwater-Surface Water Interface of a Degraded Urban Stream, *J. Environ. Qual.*, 39, 810-823, 2010.

Mulholland, P. J., Marzolf, E. R., Webster, J. R., Hart, D. R., and Hendricks, S. P.: Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams, *Limnology and Oceanography*, 42, 443-451, 1997.

Pennino, M. J., Kaushal, S. S., Beaulieu, J. J., Mayer, P. M., and Arango, C. P.: Effects of urban stream burial on nitrogen uptake and ecosystem metabolism: implications for

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watershed nitrogen and carbon fluxes, *Biogeochemistry*, 121, 247-269, 2014.

Poff, N. L., Bledsoe, B. P., and Cuhaciyan, C. O.: Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems, *Geomorphology*, 79, 264-285, 2006b.

Roley, S. S., Tank, J. L., and Williams, M. A.: Hydrologic connectivity increases denitrification in the hyporheic zone and restored floodplains of an agricultural stream, *Journal of Geophysical Research-Biogeosciences*, 117, 16, 2012.

Sudduth, E. B., Hassett, B. A., Cada, P., and Bernhardt, E. S.: Testing the Field of Dreams Hypothesis: functional responses to urbanization and restoration in stream ecosystems, *Ecological Applications*, 21, 1972-1988, 2011a.

US EPA: Section 319. Nonpoint Source Program Success Story: Maryland. Restoring Stream Reduces Nitrogen in an Urbanized Watershed, EPA 841-F-09-001KK, 2009. 2009.

A clearer link between results and conclusions should be made. At the moment the results and their interpretation do not support conclusions and implications. It is more what you would want your study to show. Based on our collective revisions there is now a clearer link between the results and the conclusions.

Finally, the paper needs language revision to remove not very scientific expressions as those highlighted above. As mentioned above, we have now revised the language to make the paper more clear.

Please also note the supplement to this comment:

<http://www.hydrol-earth-syst-sci-discuss.net/12/C7072/2016/hessd-12-C7072-2016-supplement.pdf>

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